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URANIUM-BEARING SANDSTONE DEPOSITS OF THE COLORADO PLATEAU.[1]

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ABSTRACT.

The uranium-bearing sandstone deposits of the Colorado Plateau are commonly referred to as "carnotite deposits." They have been the principal domestic source of uranium, radium, and vanadium. The deposits are largely restricted to a few stratigraphic zones, along which they have a wide but spotty areal distribution. The ore minerals mainly impregnate sandstone, though in places fossil plants are richly mineralized. Most of the ore bodies are small, but have a wide range in size, and within individual deposits the ore has a considerable range in thickness and grade. The deposits are irregularly tabular or lenticular, with their long axes nearly parallel to the bedding, but the ore does not follow the beds in detail.

The ore is thought to have been precipitated from ground-water solutions after the enclosing sands had accumulated and before regional deformation. Sedimentary structures that seem to have controlled the movement of these solutions and the features that probably localized the ore deposits are described, and their application as guides to ore finding is explained.

INTRODUCTION.

SANDSTONE deposits containing uranium, radium, and vanadium are widely distributed in the Colorado Plateau and have been the principal domestic source of these metals. They are commonly referred to as "carnotite deposits." The total value of the vanadium and radium obtained from them

[1] Published by permission of the Director, U. S. Geological Survey, and presented before the Society of Economic Geologists, San Francisco, February 1949.

probably exceeds $75,000,000; likely no true market value can be assigned to the uranium produced in recent years.

The carnotite deposits were discovered in 1899, but only a small amount of ore was produced during the next decade. From 1910 to 1923 many of the deposits were worked for the radium they contained, and some vanadium and uranium were recovered as byproducts. Although some of the deposits were mined from 1924 to 1936, mainly for vanadium, most of them were idle, but from 1937 through the war years the deposits were intensively worked, again mainly for vanadium. During this last period of operation most of the ore averaged slightly less than 2 percent V_2O_5 and about 0.25 percent U_3O_8.[2] Many of the carnotite deposits are now being worked for uranium and vanadium.

The carnotite deposits have many interesting geologic features, some of them essentially unique among metallic ore deposits. This paper describes briefly the general character of the deposits and emphasizes a few features useful in ore finding. The work being done on the Colorado Plateau by the U. S. Geological Survey is also described briefly. The reader desiring a more detailed description of the deposits is referred to the reports listed in the selected bibliography at the end of this paper.

ORE DEPOSITS.

Nearly all of the carnotite deposits of the Colorado Plateau are in sandstones of Mesozoic age; most of the deposits are restricted to a few stratigraphic horizons, along which they have a spotty distribution. The ore mainly impregnates sandstone, but some of the fossil plant material in the ore-bearing beds is richly mineralized. Ore bodies range from small irregularly shaped masses only a few feet across, containing only a few tons of ore, to large tabular bodies as much as several hundred feet across, containing many thousand tons of ore; most deposits contain less than a thousand tons each. The tabular bodies are irregular in thickness and plan. Though their long dimensions are nearly parallel to the bedding in the sandstone, the ore layers do not follow the beds in detail. For this reason, the ore in its present form cannot be syngenetic but must have been precipitated from solutions after the sands had accumulated.

The structural environment of the carnotite deposits differs from place to place. The ore-bearing and associated beds in general dip at low angles, having been tilted in broad folds, but some typical deposits occur in steeply dipping beds, whereas others occur in horizontal beds several miles from areas of deformation. High-angle faults with displacements ranging from a few inches to a hundred feet or more are common locally, but neither the distribution of the deposits in general nor the character of individual deposits seems to be genetically influenced by fracturing. All faults displace the ore and are thought to be post-mineral. Though the ore-bearing strata have been invaded in places by igneous intrusions, the deposits on the whole seem to be dis-

[2] Huleatt, W. P., Hazen, Scott W., Jr., and Traver, William M., Jr., Exploration of vanadium region of western Colorado and eastern Utah: U. S. Bur. Mines Rept. Inv. 3930, p. 8, 1946.

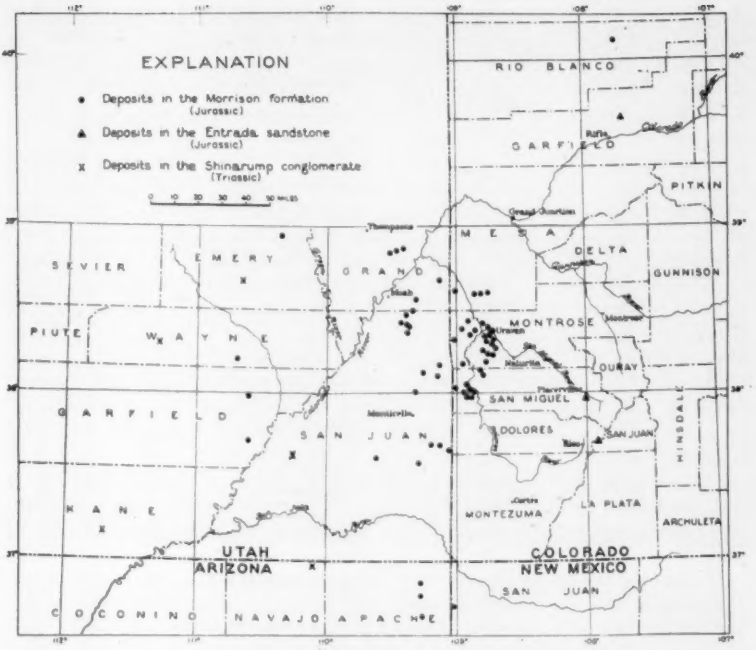

FIG. 1. Index map of part of Colorado, Utah, Arizona, and New Mexico, showing the general distribution of carnotite-bearing deposits.

tributed without regard to these intrusives, and many are miles from any known igneous activity. Furthermore, the mineral composition of the deposits is not similar to those of hydrothermal ores. Considering all factors, it is difficult to rationalize the localization and character of the deposits as originating from hydrothermal or ground-water solutions that were introduced into the beds along cross-cutting structures that resulted from regional deformation.

On the other hand, the habits of the ore and the location of the deposits show a close relationship to sedimentary structures and conditions that at one time or another would certainly have influenced the flow of ground waters through the ore-bearing beds. Recognizing these features, and believing that mineralization after regional deformation is unlikely, the writer therefore suggests that the ore was precipitated from ground waters that moved along the beds during a period of active circulation shortly after the sands accumulated. Precipitation probably was caused by relatively slight changes in composition of the waters.

The general distribution of the carnotite-bearing deposits is shown on the index map, Figure 1. All have many common characteristic features even

though their size, form, and geologic environment differ somewhat from place to place. Most of those in the Shinarump conglomerate, of Triassic age, are in central Utah and northern Arizona, and none of them have been very productive. Recently some deposits containing uranium and copper, with little or no vanadium, have been found in the Shinarump conglomerate in southeastern Utah. Near Rifle, Placerville, and Rico, Colo., the Entrada sandstone of Jurassic age is host to important deposits of vanadium ore, but these deposits contain only a small amount of uranium. Most of the deposits are in the Morrison formation, of Jurassic age, and the following description, as well as most of the work being done on the Colorado Plateau by the U. S. Geological Survey, applies particularly to these deposits.

The ore is mainly an impregnation of sandstone. The principal vanadium mineral is micaceous and forms minute flakes that coat the sand grains and partly or completely fill the pore spaces of the sandstone (Fig. 2). This mineral colors the rock gray, and the color darkens as the vanadium content increases. Dark-colored vanadium oxides and brightly colored calcium vanadates are also present in places. Carnotite is the principal uranium mineral. It is bright yellow and occurs disseminated in the sandstone; it also richly replaces fossil wood.

Figure 3 shows a typical face of ore. The ore layer is about 2 feet thick and crosses the bedding at a low angle. Minor concentrations of vanadium occur along favorable bedding planes, as indicated by the darker shades of gray.

In general the ore grades into the enclosing sandstone, as shown by Figure 3, but commonly the limits are fairly well defined and in places sharply defined. The lack of conformity of the ore layers with the bedding is most conspicuous where the limits are well-defined, for the edge of ore is a nearly smooth surface that is gently undulant or curves across the bedding at high angles. Wherever the ore layer, or even one edge of it, crosses the bedding in a smooth curve, the feature is called a "roll" by the miners. Rolls are easily recognized in the field, though their forms and variations are difficult to describe. They have many concretionary habits. Some are nearly cylindrical, whereas others are crescent-shaped or "S"-shaped in cross section. Nearly all are elongate, mostly ranging from 10 to 100 feet in length, but a few rolls as much as several hundred feet in length have been found. Most rolls in a single ore body, and in neighboring ore bodies as well, trend in about the same direction. Ore bodies are elongate in the direction of the roll trend.

Figure 4 shows a photograph of a mined-out roll. The roll was at least 75 feet long and had a fairly consistent shape over its entire length. The unmined sandstone adjacent to the roll is barren.

Figure 5 shows the detail of an edge of a roll. The sandstone bedding is nearly flat and the edge of ore is well-defined and crosses the beds at a high

FIG. 2. Photomicrograph of sandstone impregnated with the micaceous vanadium mineral (dark). × 95.

FIG. 3. Typical face of vanadium ore. The ore (dark) is composed mainly of the micaceous vanadium mineral, in part disseminated in the sandstone and in part concentrated along bedding planes. The pocket watch indicates the scale. Club mine, Montrose County, Colorado.

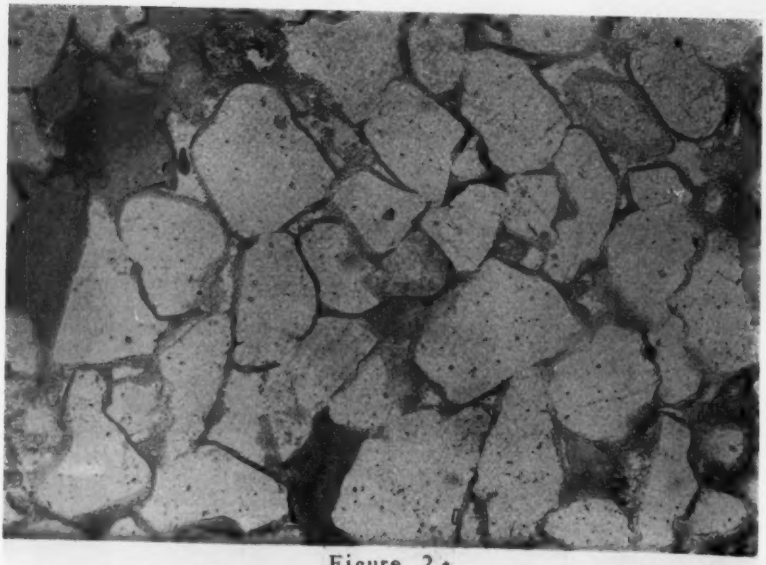

Figure 2.-

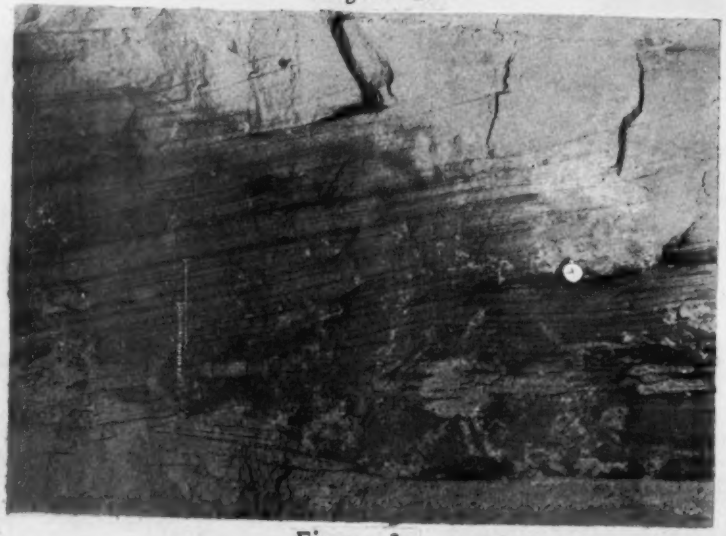

Figure 3.-

Figure 4.-

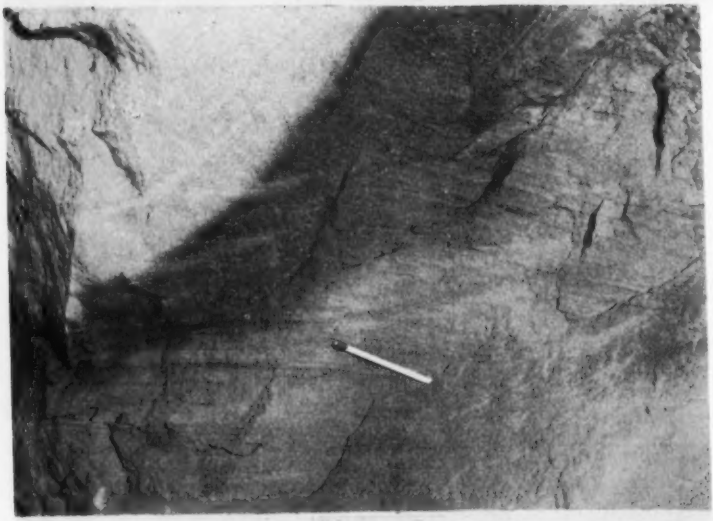

Figure 5.-

angle and in a smooth curve. The light-colored sandstone adjacent to the ore is barren of vanadium.

Figure 6 shows the character of mine workings and the general shape of ore bodies. It also shows the position and orientation of the ore rolls and the orientation of the fossil logs in the ore-bearing sandstone. At most places fossil logs have a local common orientation; here they all trend northeast. As the logs were rafted into place, and as they parallel the trend of the sandstone lenses or channel-fills, their orientation must have been controlled by the stream currents that deposited the enclosing sands. Here and nearly everywhere else, the rolls have a dominant trend parallel to the orientation of the logs.

GUIDES TO ORE FINDING.

The Morrison sandstone beds containing the ore deposits are lenticular and in places 50 feet or more thick. They are interbedded with mudstone. The sands were deposited in channels and on flood plains of streams that meandered widely across a surface of low relief and grade. Most of the carnotite deposits seem to occur in or near the thicker, central parts of the lenses; the portions of the channel sands that occupy meander bends seem to be particularly favorable for ore deposits in some areas. In places the channel sands form well-defined lenses, some only a few hundred feet across, and these can be recognized at the outcrop or in cross sections through drill holes. Other sandstone lenses are broad and vaguely defined. The trend of the channel sands commonly can be determined by observations of bedding and, locally, by the orientation of the fossil logs. In places the channels can be projected and followed, though caution must be used in projection, for some of the channel sands seem to have frayed out along their course and others were cut off by later channels. Furthermore, overlying beds and even the upper part of the ore-bearing bed might not have accumulated in a stream flowing in the exact direction of flow of the stream in which the lower, more favorable part of the ore-bearing bed was formed. Therefore, observations at the surface commonly do not reveal the trend of underlying beds. The sandstone in the central parts of the channels is dominantly medium-grained, medium- to thick-bedded or irregularly bedded, and moderately clean, although some mudstone in the form of grains, pebbles, and small lenses is common. Lenses of sandstone less than about 20 feet thick, which might have been deposited in small or short-lived channels or on flood plains bordering the main channels, rarely contain sizable ore deposits. Such sandstone is dominantly fine-grained, thin-bedded, and either clean or argillaceous.

FIG. 4. Photograph of a mined-out roll. A small pillar of ore (gray) remains behind and to the right of the survey rod, which is divided into 1-foot intervals. The unmined sandstone to the right and left of the roll and above the mined-out ore-bearing layer is barren. Club mine, Montrose County, Colorado.

FIG. 5. Close-up photograph of an edge of a roll, showing the edge of ore (dark) crossing bedding at a high angle; the light-colored sandstone in the upper left is barren. The match is used to indicate scale. Club mine, Montrose County, Colorado.

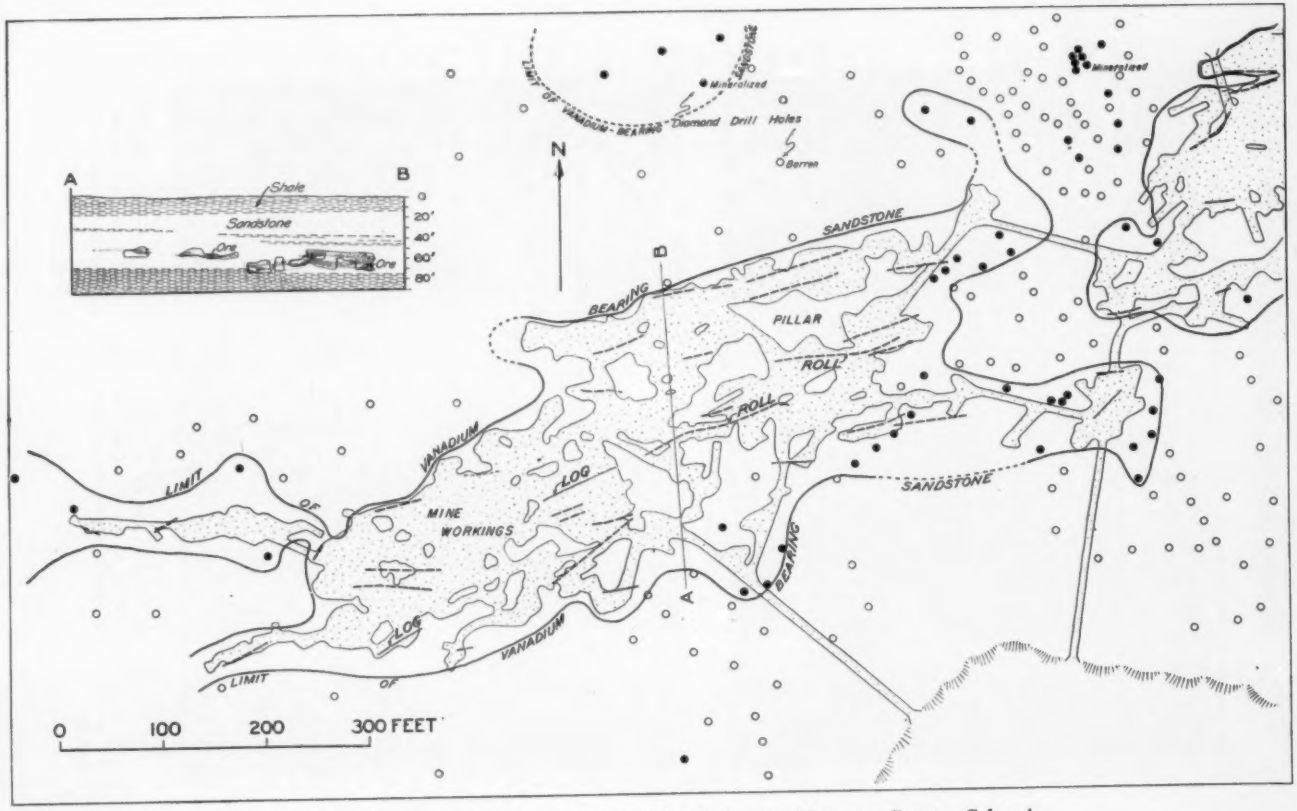

FIG. 6. Geologic map and section of part of the Club mine, Montrose County, Colorado.

As a working hypothesis to explain the observed associations of the deposits to the channel sands, it is assumed that ground waters moving along the beds would follow mainly the central parts of the sandstone lenses, owing to the effect of greater thickness and greater permeability. Even so, the route of ground waters moving along discontinuous lenses would be devious and in places might be controlled by other factors that may not be recognizable. Nevertheless, the sandstone beds and the associated mudstone have characteristic colors in the vicinity of ore deposits, and these colors probably express the effect of circulating solutions. The sandstone enclosing most ore bodies is dominantly pale to light yellow brown and it is speckled with limonite stain. Sandstone that is whitish to pale yellow brown or that which is reddish brown contains few deposits and most of them are small. The mudstone that is interbedded with this sandstone, as well as the grains, pebbles, and lenses of mudstone within the sandstone, is dominantly red, which is believed to have been its original color. Near ore deposits, however, the mudstone within the ore-bearing sandstone and the upper few inches to few feet of the mudstone beneath the ore-bearing sandstone are altered to gray (the so-called "blue clay" of the miners). Although the character and cause of this color change are not clearly understood, the presence of considerable altered mudstone in the ore-bearing sandstone and immediately below it is probably the most useful guide in recognizing ground favorable for ore deposits.

Thus it appears that sedimentary conditions were largely responsible for preparing ground for ore and that the route of the moving ground waters—probably the ore-bearing solutions themselves—is indicated by the color of the sandstone and particularly by the altered color of the associated mudstone.

GEOLOGICAL SURVEY WORK ON THE COLORADO PLATEAU.

The Geological Survey is conducting a long-range program of diamond-drill exploration for carnotite ore and of geologic studies of these deposits. The plan of this work is based on a general directive from the U. S. Atomic Energy Commission, on whose behalf the work is being done.

Exploration.—The principal objective of the exploration work is to find unknown deposits that might result in the development of new mines and will yield the reserves needed to sustain future milling operations. The purpose of most of the drilling is to test ground away from known deposits, ground that has not been tested and probably will not be tested by private industry because of the high risk of poor yield, rather than to look for extensions of known deposits that might ultimately be developed by owners under the stimulus of favorable economic conditions. The exploration thus is mainly of "wildcat" character, and less favorable results are to be expected from it than from drilling near known deposits and coordinated with mining operations.

Areas to be explored are selected by the Geological Survey on the basis of geologic favorability. At the request of the Atomic Energy Commission, the right of mineral entry has been and will be withdrawn from the areas selected for exploration, in order to avoid speculative staking of claims during drilling operations. Within the areas selected for drilling, and after the right of mineral entry has been withdrawn, exploration agreements are obtained

FIG. 6. Geologic map and section of part of the

from the owners of privately held mining claims, and the land held for other purposes as well, before drilling begins.

Although the plan of exploration varies to some extent from place to place, depending upon known conditions and those encountered in drilling, in general it comprises the following three stages.

Stage 1, drilling for geologic information: Fairly large areas that, on the basis of geologic conditions, are thought to be reasonably favorable for ore are first drilled with a pattern of widely spaced holes, primarily for geologic information. It is hoped, though not yet proved, that ground which is geologically favorable for ore can be recognized with widely spaced drilling and that it will be possible to eliminate unfavorable ground where drilling on closely spaced patterns would be less productive or fruitless.

Stage 2, drilling for ore deposits: Within ground that is geologically favorable for ore, holes are drilled at a moderate spacing, approximately 200 feet apart. The interval and pattern are planned to cut with at least one hole each, all or nearly all of the deposits of average size that can be expected in the area. For success at this stage of work the drill need not cut ore of commercial grade and thickness—the weakly mineralized sandstone and the thin layers of ore that commonly extend beyond the limits of commercial bodies offer a larger target and a lead to ore bodies if any are present.

Stage 3, drilling for partly outlining deposits: Where ore or a show of mineralized rock is cut by a hole drilled in stages 1 or 2, usually four off-set holes are drilled about 50 feet from the discovery hole, with the hope that any extension of the lead in that hole will be cut. Where an extension is proved by one or more holes, other holes are drilled in the general direction of the extension at about 100-foot intervals until the deposit is roughly outlined.

Several factors of non-geologic character influence the amount and pattern of drilling used in stage 3. On privately owned property, where it is thought that enough ore was cut by the discovery hole or in one or more off-sets to encourage the owner to continue development, drilling is discontinued. On government land, where it is expected that mining will be done under lease arrangements, the deposit is tested with a few more holes than under a similar condition on privately owned ground. Where ore is encountered so near the surface that it can be cheaply tested with jackhammer drilling or by an open-cut with a bulldozer, diamond drilling is discontinued.

Geologic Studies.—Although diamond-drill exploration specifically for carnotite ore was not started by the Geological Survey until November 1947, during 1943 the Geological Survey and the Bureau of Mines cooperated in drilling for vanadium ore in this region. Previously, in 1939, the Geological Survey had begun comprehensive geologic studies of the carnotite deposits and continued them through the war years. Of these studies, regional mapping and stratigraphic investigations are continuing intensively today. Mineralogic studies beyond those already done are also planned, as well as a study of past and present ground-water conditions in the ore-bearing rocks. In addition, plans to develop geophysical and geochemical methods of prospecting are being considered. The geologic studies are closely integrated with exploration and are aimed to determine the possible source of the metals in the

carnotite deposits, the mode and route of transportation of these metals, and the conditions favorable for the localization of the ore deposits, as a guide to ore finding and an aid in evaluating the resources of the region.

U. S. GEOLOGICAL SURVEY,
GRAND JUNCTION, COLO.,
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URANIUM IN PEGMATITES[1]

LINCOLN R. PAGE.

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ABSTRACT.

Uranium and rare-earth minerals are common accessory minerals in pegmatite deposits. No domestic pegmatites have been found that are rich enough to support an economic mining operation for uranium alone; however, small quantities of uranium minerals may be recovered as by-products of feldspar or mica mining. Madagascar is the only country that has produced appreciable tonnages of uranium minerals from pegmatites.

A review of the literature and observations in the domestic pegmatite districts show that the uranium and rare earth minerals generally occur in pegmatites or pegmatite units rich in potash feldspar. Recent mineralogical and structural studies of pegmatites by the U. S. Geological Survey indicate that, on the basis of geologic mapping, these units can be projected laterally and in depth with reasonable accuracy. In most places the mineral content of these units can be estimated with sufficient accuracy for development purposes.

INTRODUCTION.

URANIUM minerals are common minor constituents of pegmatite deposits, in the United States and other parts of the world, and they commonly are closely associated with rare-earth minerals. Ellsworth[2] notes 71 uranium minerals and 72 rare-earth minerals, some of which may contain small amounts of uranium. Most of these 143 minerals have been recognized in pegmatites from various parts of the world, but they rarely occur in sufficient quantities to be economically important as a source of uranium.

[1] Published by permission of the Director, U. S. Geological Survey, and presented before the Society of Economic Geologists, San Francisco, February 1949. All information in this paper relative to foreign occurrences of uranium has been obtained solely from material already published.

[2] Ellsworth, H. V., Rare element minerals of Canada: Dept. of Mines, Geol. Survey, Econ. Geol. series 11, pp. 45–53, 1932.

The Madagascar pegmatites are the only ones that have furnished appreciable tonnages of uranium minerals. Hess [3] records the production and sale of over 100 tons of euxenite and betafite ores from Madagascar, together with about 37 tons of autunite and uranocircite ores recovered from peat beds, but probably derived indirectly from pegmatites. The production from other parts of the world has been limited, for the most part, to lots of a few tens of pounds or a few tons of uranium-bearing minerals that were produced as byproducts during mining for mica and feldspar.

The study of uranium minerals in domestic pegmatites has been carried on by the U. S. Geological Survey as part of its comprehensive investigation of pegmatites. During and after World War II more than 70 man years of work were spent on the investigation of sheet mica, beryl, lithium, columbium, and tantalum deposits in all of the major pegmatite districts of this country. Many occurrences of uranium and rare-earth minerals were examined briefly, and it appears possible to point out, at this time, the types of pegmatites or pegmatite units most likely to contain uranium minerals. None of the known domestic deposits contains a sufficient quantity of uranium minerals to warrant mining for uranium alone, but it is possible that small quantities may be recovered from time to time as byproducts of mining for other pegmatite minerals. Until large tonnages of pegmatite are mined and milled, the yearly production will continue to be, at the most, only a few hundred pounds or a few tons per year, and even if milling of pegmatite ores were to become a common practice, the production from pegmatites probably will remain comparatively small.

The writer wishes to acknowledge the work of other members of the Geological Survey used in preparing this paper. It is impossible to give specific credit to all the men who have contributed to the development of the ideas expressed in this paper. Special credit should be given to John B. Hanley, who, under the writer's direction, mapped and studied the Bob Ingersoll pegmatites, Keystone, S. Dak., and the Hyatt Beryl pegmatite, Larimer County, Colo.; and to James J. Page, who furnished most of the data presented in descriptions of the Ruggles and Palermo mines in New Hampshire. The assistance of Mr. Michael Fleischer and Mr. Vincent McKelvey, who critically reviewed the manuscript, is gratefully acknowledged.

MINERALOGY.

The uranium minerals that occur in pegmatites may be grouped, on the basis of origin, as primary and secondary. The primary uranium minerals include (a) simple oxides; (b) multiple oxides containing columbium, tantalum, and titanium; (c) miscellaneous compounds; and (d) carbonaceous materials. All the primary minerals commonly are partly or completely altered to yellow, green, orange, and red secondary minerals. These secondary minerals are imperfectly known, but probably there are 50 or more mineral

[3] Hess, F. L., Cobalt, molybdenum, nickel, tantalum, titanium, tungsten, radium, uranium, and vanadium in 1922, in 1923, in 1924: U. S. Geol. Survey, Mineral Resources, 1922, pt. 1, pp. 557–583, 1924; U. S. Geol. Survey, Mineral Resources, 1923, pt. 1, pp. 235–258, 1924; U. S. Bur. Mines, Mineral Resources, U. S., 1924, pt. 1, pp. 451–476, 1926.

species,[4] including hydrated oxides, carbonates, phosphates, arsenates, sulfates, and others. Table 1 gives the physical properties and chemical compositions of the more common uranium-bearing mineral series, species, and varieties found in pegmatites.

Primary Minerals.—The primary simple oxides include the partly isomorphous minerals uraninite and thorianite. Uraninite, however, is the only one that is common in pegmatites. It characteristically occurs in muscovite-rich pegmatite in close association with potash feldspar, plagioclase, and quartz.

Many of the more common primary uranium minerals belong to a group of complex oxides that are essentially columbates-tantalates-titanates of sodium, calcium, rare earths, thorium, and uranium. They are not well characterized, not easily identified, and their formulas are uncertain. Among the most common are samarskite and members of the euxenite-polycrase, eschynite-priorite, pyrochlore-microlite, fergusonite-formanite, and betafite series. All of these, except members of the pyrochlore-microlite series, occur in the potash-feldspar-rich parts of pegmatites, where they are associated with muscovite, albite, and quartz. The pyrochlore-microlite minerals are most abundant in lepidolite-bearing pegmatites.

In addition to the simple and complex oxides of uranium there are several rare-earth phosphates, such as monazite and xenotime, and silicates, such as allanite, tscheffkinite, zircon (cyrtolite), and gadolinite, that may contain uranium. The most common of these, monazite, is usually associated with samarskite or euxenite in potash-feldspar-rich pegmatites. Allanite, on the other hand, occurs in biotite-rich pegmatites, together with muscovite, plagioclase, and potash feldspar. The quantity of uranium in these minerals is normally so small that they are not likely to become ores of uranium.

Thucholite and anthraxolite are carbonaceous materials, probably not minerals, that occur in some pegmatites, closely associated with uraninite.

Secondary Minerals.—Most primary uranium minerals are partly or completely altered to hydrated oxides, phosphates, arsenates, sulfates, silicates, vanadates, and carbonates. These are brightly colored, yellow, green, or reddish-orange compounds of variable water content. In large part they are apparently the result of alteration associated with the late stages of pegmatite formation rather than weathering. Gummite and its varieties, all of uncertain composition, are the most abundant secondary minerals in pegmatites. Gummite is commonly pseudomorphous after uraninite. It forms an orange to reddish layer around the unaltered mineral and grades outward into yellowish or greenish uranium minerals such as autunite, uranophane, phosphuranylite, or uranocircite. These alteration products are in part transported outward from the primary minerals and deposited as thin crusts or flakes along cracks and fractures in the adjacent rock. Torbernite, the copper-bearing uranium phosphate, is a common encrustation on cracks and fractures in pegmatite and appears to have been derived, at least in some cases, from the primary minerals. The secondary uranium-bearing arsenates, sulfates, carbonates and vanadates are not common in pegmatites.

[4] Fleischer, Michael, Personal communication.

INTERNAL STRUCTURE OF URANIUM PEGMATITES

Uranium-bearing pegmatites, like pegmatites containing deposits of mica, beryl, spodumene, lepidolite, feldspar, or columbite-tantalite, are composed of units of contrasting mineralogy, texture, or both. These units have been classified as zones, fracture filling units, and replacement units.[5]

Zones are shell-like or lenticular units that parallel the pegmatite-wall rock contact and are roughly concentric around an innermost unit or core. For the most part the size, shape, and position of their downward and lateral extensions are predictable. For convenience in describing mineral deposits, zones have been divided into four main types as follows, in sequence inward from the contact to the center of the pegmatite: (1) border zone, (2) wall zone, (3) intermediate zone, and (4) core.

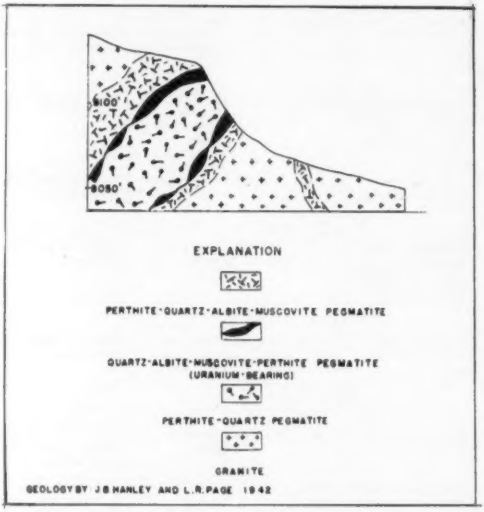

FIG. 1. Cross section, Hyatt Beryl pegmatite, Larimer County, Colo.

Fracture-filling units are tabular or veinlike bodies that fill fractures in pre-existing pegmatite. The minerals of these units may or may not be zoned in relation to their contacts. Downward and lateral extensions are predictable within the limits expectable for fracture-filling veins.

Replacement units are irregular to lenticular bodies which cut across other pegmatite units and contain relict structures, textures, and rarely individual minerals of pre-existing *pegmatite*. Their extensions normally are not predictable, except where controlled by such structural features as fractures or gneissoid banding.

[5] Cameron, E. N., Jahns, R. H., McNair, A. N., and Page, L. R., Internal structure of granitic pegmatites: ECON. GEOL., Mon. 2, Oct. 1949.

TABLE 1.—PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF

Mineral	Physical properties					
	Form	Hardness	Specific gravity	Luster	Color	General formula and major elements
Primary minerals Oxides[1] Uraninite	Octahedral and cubic crystals, massive, botryoidal, banded	5–6	8.0–10.0	Submetallic, pitchlike, greasy, dull	Steely to velvety black, brownish black, grayish, greenish	UO_2. Natural material always oxidised. Composition is $U_{3-4}O_9$. Also contains Th, Pb
Thorianite	Cubic crystals	6.5	9.7	Horny to submetallic	Dark gray to brownish black, black	ThO_2
Multiple oxides, containing Cb, Ta, Ti[1] Euxenite-polycrase series	Stout prismatic, parallel, subparallel and radial aggregates of crystals, massive	5.5–6.5	5.0–5.9	Brilliant, submetallic, greasy, vitreous	Black, greenish to brownish	AB_2O_6 A = Y, Ce B = Ti, Cb, Ta
Eschynite-priorite series (includes blomstrandinite)	Prismatic to short prismatic, tabular, massive	5–6	4.9–5.2	Submetallic, resinous, waxy	Black, yellowish or brownish black	AB_2O_6 A = Ce, Th, Y, Er B = Ti, Cb
Samarskite	Prismatic with rectangular cross sections. Also tabular, elongate, massive. Crystals rough	5–6	5.7–6.2	Vitreous, resinous	Velvet black, brownish black	Probably AB_3O_8 A = Y, Er, U, Fe[2] B = Cb, Ta
Betafite series Betafite	Octahedral flattened or elongate	4–5.5	3.7–5.0	Waxy, vitreous, semimetallic	Greenish brown, yellow to black	$AB_2O_6\ nH_2O$ A = U, Ca B = Cb, Ta, Ti
Ampangabeite	Short rectangular prisms	4	3.36–4.64	Horny or fatty	Light-yellow brown to deep brown and brownish black	$A_2B_7O_{18}$ to AB_6O_{14}? A = U B = Cb, Ta, Fe[2], Ti
Pyrochlore-microlite series	Octahedral crystals, irregular masses and grains	5–5.5	4.2–6.4	Vitreous, resinous	(Pyrochlore) Brown to black, often yellowish, reddish, or blackish brown. (Microlite) Pale yellow to brown, hyacinth red, olive buff or green	$A_2B_2O_6$ (O, OH, F) A = Na, Ca, Fe[2], Mn[2], Ce, Th, Zr, U B = Cb, Ta, Ti
Fergusonite-formanite series	Prismatic, irregular masses and grains	5.5–6.5	5.6–5.8	Dull, brilliantly vitreous, submetallic	Gray-yellow, brown, dark brown, brownish black, velvety black	ABO_4 A = Y, Er, U[4] B = Cb, Ta
Miscellaneous[2] Monazite	Monoclinic, tabular crystals	5–5.5	4.9–5.3	Resinous	Hyacinth red, clove brown, reddish or yellowish brown, golden, golden-blue, colorless	(Ce, La, Di)PO_4

[1] Palache, Charles; Berman, Harry; Frondel, Clifford; Dana's system of mineralogy, 7th edition, vol. 1, New York, John Wiley and Sons, Inc., 1944.

[2] Except where noted data are from Dana, E. S., and Ford, W. E., Textbook of mineralogy,

THE MORE COMMON URANIUM-BEARING MINERALS IN PEGMATITES

Chemical composition				Varieties	Remarks
Minor elements	Admixed and questionable elements	Approximate percentage of uranium oxides	Approximate percentages of ThO_2		
Zr(?), Ta(?), rare earths, He, N, A	Ti, Mn, Bi, P, As, Si, Al, Fe, alkaline earths, alkalies, H_2O probably secondary	63 to 93	<14	(a) Crystallized:—Uranoniobite, Ulrichite Varieties:—Thorian (bröggerite) Cerian and Yttrian (cleveite, nivenite) (b) Massive, colloform:-Pitchblende	Specific gravity of pitchblende is 6.5–8.5
Pb, Ce, La, Fe^3(?), Zr(?), He	H_2O secondary	<38	<03	(a) Uranoan	Very rare
A = Ca, U, Th B = Fe^3 Others = He, N, Hf, Ge, Sc	Si, Al	<14	<5	(a) Tantalian euxenite and tantalian polycrase	Polycrase is the Ti-rich end. Euxenite is the Cb, and Ta end of the series. Generally Cb > Ta. Cb predominates in series
A = Ca, Fe^3, Mn, Pb, U, Sn, Zr B = Ta, Al, Si Others = He, N, Ra	Minor elements in part admixed	<6	<18		Y and Er substitute for Ce in priorite. Th most abundant in eschynite
A = Ce, La, Ca, Th, Pb, Di B = Ti, Sn, W, Zr(?) Others = He, N, Ra	Si, H_2O probably secondary	<17	<4	Plumboniobite. Wiikite	Commonly intergrown with columbite-tantalite
A = Pb, Th, (Y, Er), (Ce, La), Fe^3(?) B = Fe^3, Al, Sn(?)	H_2O probably secondary	<27	<2	Plumbian (Samiresite). Blomstrandite. Mendelejevite. (Mendelyeevite, Mendeleyevite) Titanian betafite	Betafite-greenish brown. Samiresite-yellow. Titanian-black. Djalmite is possibly the tantalum equivalent of betafite
A = Y, Er, Ca, Th, Ce(?), La(?), Di(?) B = Sn(?)	H_2O probably secondary	<20	<2		May be an inhomogeneous alteration product
A = K, Mg, Sb, Pb(?), La, Di, Er, Y B = Sn(?), Fe^3(?), W(?) Others = Si, Hf	Some of the minor elements may be admixed	<19	<5(<7.67)	Uranian: Hatchettolite. Ellsworthite Also titanian, cerian, ferroan, and ferrian	Pyrochlore is essentially $NaCaCb_2O_6F$ and microlite is $(Na, Ca)_2Ta_2O_6(O, OH, F)$
A = Ce, La, Di, Zr, Th, Ca, Fe^3 B = Ti, Sn, W Others = F, N, Ra	H_2O secondary	<8	<5	Titanian, uranian, and erbian	Fergusonite is the Cb end and formanite the Ta end of the series. A is principally Y, Er, Ce, Fe in fergusonite and U, Zr, Th, Ca in formanite
Th, Si, U, Y, Fe, Al, Ca	Th and Si(?)	<1[1]	<13[1]		

3d edition, New York, John Wiley and Sons, Inc., 1926.

[1] Ellsworth, H. V., *op. cit.*, pp. 178–179, 266.

TABLE 1.—

Mineral	Physical properties					
	Form	Hardness	Specific gravity	Luster	Color	General formula and major elements
Xenotime	Square prisms, tetragonal crystals	4–5	4.45–4.56	Resinous to vitreous	Yellowish brown, reddish brown, hair brown, flesh red, grayish white, wine yellow, pale yellow	YPO_4
Allanite	Monoclinic plates, tablets, needles	5.5–6	3.0–4.2	Submetallic, pitchy, resinous	Brown to black	HAB Si_2O_{13} A = Ca, Fe^2 B = Al, Fe^3, Ce, Di, La, Y
Tscheffkinite	Massive	5.0–5.5	4.5–4.55	Vitreous	Velvet black, red brown	Titano-silicate of iron, calcium, cerium metals, etc.
Zircon (cyrtolite)	Square prisms	7.5	4.68–4.70	Adamantine	Colorless, orange, pale yellowish, grayish, yellowish green, brownish yellow, reddish brown	$ZrSiO_4$
Gadolinite	Monoclinic prisms	6.5–7.0	4.0–4.5	Vitreous, greasy	Black, greenish black, brown	$Be_2FeY_2Si_2O_{10}$
Carbonaceous "minerals"[2] Thucholite	Nodules, squarish cross sections	3.5–4.0	1 777	Brilliant	Black	Formula unknown. Contains U, Th, Si, Ce, La, Di, Y, Er, C, H
Secondary minerals[2] Gummite[1]	Massive, dense, crusts, pseudomorphs	2.5–5	3.9–6.4	Greasy, waxy, vitreous, brilliant to dull	Yellow, orange, reddish yellow to orange red, hyacinth red, reddish brown to brownish black, black	Approximately UO_3nH_2O with Pb, Th, H_2O
Uranocircite	Tablets[3]	2	3.53[4]	Pearly[4]	Yellow green	$Ba(UO_2)_2P_2O_8 \cdot 8H_2O^2$ $Ba(UO_2)_2As_2O_8 \cdot 12(?)H_2O^5$
Autunite	Thin tablets, micaceous masses	2–2.5	3.05–3.19	Pearly, subadamantine	Lemon to sulfur yellow	$Ca(UO_2)_2P_2O_8 \cdot 8H_2O$
Torbernite	Square tabular, thin crystals. Micaceous masses	2–2.5	3.4–3.6	Pearly, subadamantine	Emerald green, grass green, less commonly leek, apple, and siskin green	$Cu(UO_2)_2P_2O_8 \cdot 12H_2O$
Phosphuranylite	Pulverulent encrustations. Tablets[3]	Soft		Pearly[4]	Lemon yellow	$(UO_2)_2P_2O_8 \cdot 6H_2O$
Rutherfordite	Finely fibrous[3]	Soft	4.8		Yellow	UO_2CO_3
Uranophane	Radiating acicular prisms and fine fibrous masses	2–3[4]	3.81–3.90	Vitreous[4]	Yellow	$Ca(UO_2)_2Si_2O_7 \cdot 6H_2O$

[4] Smith, O. C., Identification and qualitative chemical analyses of minerals, New York, D. Van Nostrand Co., Inc., 1946.

Continued

Chemical composition				Varieties	Remarks
Minor elements	Admixed and questionable elements	Approximate percentage of uranium oxides	Approximate percentages of ThO_2		
Er, Ce, Si, Th		?			
U	H_2O secondary	?			
Th, Ca		?	?		Rare
Fe, U, Th, Y, and other rare earths		<2	<1		Malacon is an altered zircon. Cyrtolite is related, and carries U, Y, etc. Našgite is apparently zircon with Ta, Cb, Th, Y, U. Thorite, $ThSiO_4$, resembles zircon. Uranothorite
Er, Ce, La, Di Sc, Yb Al, Fe^2, Fe^3, Ca, Mg, Mn, Alkalies, H_2O		?	.14		Rare
Al, Fe, Ca, Mn, P, Pb, N, A, S, Cl, F, H_2O, V, Zr, Na, K		<18[3]	<11		Uraninite-thucholite (6–7%) from Quebec analyzed 68.92% U_3O_8 and 6.76% ThO_2. Often associated with cyrtolite. Anthraxolite is also composed of hydrocarbons and may contain uranium
Rare earths	Alkalies, alkaline earths, Fe^2, Al, Mn, Cu, Bi, P, C, Si	42–78	<25	Yttrian Yttrogummite Thorian	Alteration product of uraninite. Clarkeite is similar
		?			Very rare
		62.7 (theoretical)			
As may replace P		<62 56.6 (theoretical)			
		?			
		?			Alteration product of uraninite. Rare[3]
		<76		Uranotil(?)[3]	Very rare[3]

[3] Winchell, H. H., and Winchell, A. N., Elements of optical mineralogy, 2d edition, pt. 2, New York, John Wiley and Sons, Inc., 1927.

Examination of large numbers of pegmatites show that most of the internal units in pegmatites are zones. Fracture-filling units are perhaps the next most abundant. Replacement units as here defined are rare. By far the greater number of pegmatites have only a narrow border zone, usually less than 2 inches thick, and a core. A lesser number have all four structural types of zones, and a few contain fracture-filling or replacement units in addition to zones.

Eleven main mineralogic types of pegmatite zones or units have been recognized in the United States,[6] and the large number of recent detailed studies make it possible to state, with considerable assurance, the sequence and structural position of each of these zones. The sequence is based on the distribution in known pegmatites of the essential minerals—feldspars, quartz, micas, and lithium minerals. The general zone sequence is constant from pegmatite to pegmatite and from district to district, though few, if any, individual deposits contain all 11 zones. Although the accessary minerals are not considered in this sequence, they also are abundant only in certain zones or parts of zones.

In the tabulation given below the positions of the more common occurrences of uranium minerals are indicated. The zones as listed, from 1 to 11, in sequence from the wall inward are also in order according to decreasing age.

GENERAL SEQUENCE OF ESSENTIAL AND URANIUM MINERALS IN PEGMATITE ZONES (OR UNITS) IN ORDER FROM THE WALL-ROCK CONTACT INWARD TO THE CORE.

Essential minerals of the main types of pegmatite zones (or units)	Occurrence of uranium minerals in domestic pegmatites
1. Plagioclase, quartz, muscovite	Rare
2. Plagioclase, quartz	None observed
3. Quartz, plagioclase, perthite, with or without muscovite, with or without biotite	Very common
4. Perthite, quartz	Very common
5. Perthite, quartz, plagioclase, amblygonite, spodumene	Common
6. Plagioclase, quartz, spodumene	None observed
7. Quartz, spodumene	None observed
8. Lepidolite, plagioclase, quartz	Rare
9. Quartz, microcline	None observed
10. Microcline, plagioclase, lithia mica, quartz	Very rare
11. Quartz	Fairly common

Uranium or other radio-active minerals may occur in any type of structural unit, but they are most common in intermediate zones and cores; they are less common in fracture-filling and replacement units. The structurally simple pegmatites are most likely to contain uranium and rare-earth minerals if they have the mineralogical characteristics of zones 3, 4, or 11 (see above). Zones with these mineralogic assemblages are also most favorable for the occurrence of uranium in the structurally complex, or multi-unit pegmatites.

Typical of pegmatites of simple structure are some of the euxenite-bearing pegmatites in the Trout Creek Pass area, Chaffee County, Colo., that consist essentially of a single unit of coarse-grained perthite and quartz (zone 4).

The Hyatt Beryl pegmatite,[7] Larimer County, Colo. (Fig. 1) is an ex-

[6] Cameron, E. N., Jahns, R. H., McNair, A. N., and Page, L. R., op. cit.

[7] The names used in this paper with the term pegmatite serve only as a convenient means of reference and in no sense are they to be considered formal stratigraphic names.

ample of the multi-unit type of pegmatite. Uraninite and its oxidation products occur with lithiophillite-triphylite and other phosphates, beryl, and bismuth minerals in a discontinuous intermediate zone composed essentially of quartz, muscovite, perthite, and albite (zone 3 of the general sequence). This intermediate zone separates a wall zone of perthite-quartz-albite pegmatite from a core of perthite-quartz pegmatite. At the Ruggles and Palermo mines in New Hampshire uranium minerals occur in similar mineralogical and structural units. At the Ruggles mine, however, the uranium minerals are restricted to

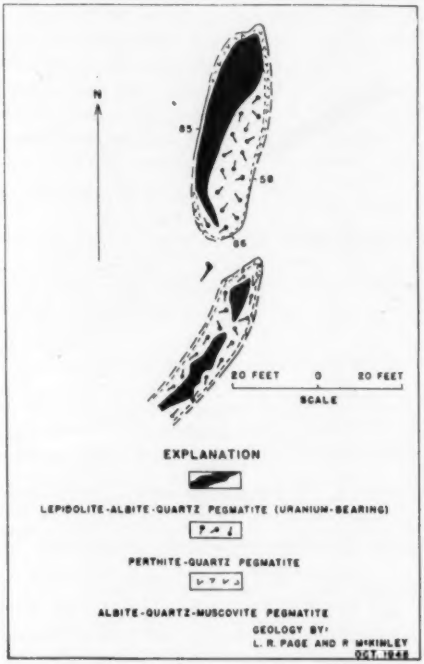

FIG. 2. Plan of the Pidlite pegmatite, Mora County, N. Mex.

the inner part of the perthite-quartz-plagioclase zone. The Brown Derby pegmatite, Gunnison County, Colo., is another structurally complex pegmatite containing uranium. Betafite is rare in the wall zone and uranium-bearing microlite occurs in the core. At the Pidlite pegmatite, Mora County, N. Mex. (Fig. 2) microlite also is present in the core.

At the Ruggles mine in New Hampshire and the McKinney mine in North Carolina, uranium minerals occur in quartz fracture-filling bodies, sometimes with muscovite and feldspar. Such deposits are generally of much smaller size than those in zones.

Replacement units of appreciable size are rare in pegmatites, and consequently few uranium deposits of this type are known. At the Bob Ingersoll Dike No. 2 pegmatite, Pennington County, S. Dak. (Fig. 3), uraninite and its alteration products occur in a fine-grained aggregate of muscovite, albite, and quartz that may be of replacement origin. This unit is between intermediate zones of quartz-albite pegmatite and perthite-quartz pegmatite.[8] Jahns [9] describes samarskite replacement units in the Petaca district, N. Mex. Cameron et al.,[10] describe the uranium-bearing unit at the Palermo mine, Groton,

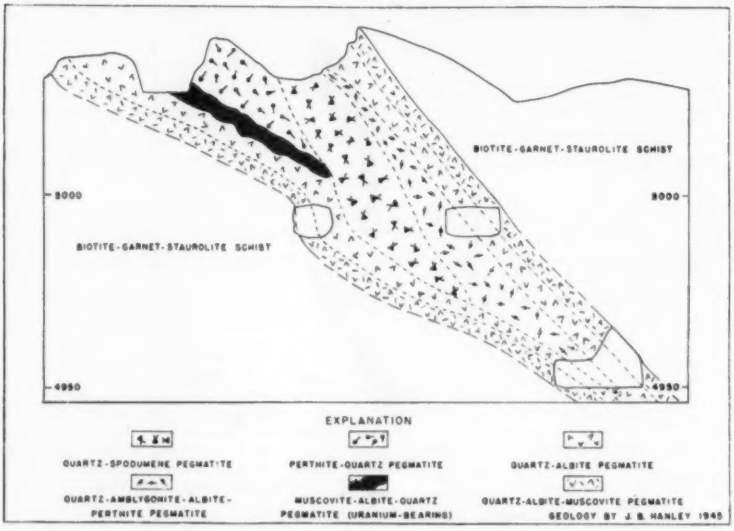

FIG. 3. Cross section, Bob Ingersoll Dike No. 2 pegmatite, Keystone, S. Dak.

N. H. as a replacement unit. Brief examinations in these localities lead the author to believe that many of these units are essentially identical to units which have been called zones in Colorado and South Dakota.

On the basis of evidence accumulated in recent years the origin of the internal structural units of pegmatites seems to be reasonably clear. Successive zones appear to have formed from the walls of the pegmatite inward by the fractional crystallization, *in situ*, of a pegmatite liquid. The early-formed crystals in any zone usually are corroded and embayed by the "rest" liquid before deposition of the younger minerals of that zone, and consequently the contacts between crystals show the relationships commonly used to prove

[8] Page, L. R., et al., Pegmatite investigations 1942–1945, Black Hills, S. Dak.: U. S. Geol. Survey Prof. Paper. (In preparation.)

[9] Jahns, R. H., Mica deposits of the Petaca district, Rio Arriba County, N. Mex.: New Mexico Bur. Mines and Min. Res., Bull. 25, 1946.

[10] Cameron, E. N., et al., Unpublished report on New England pegmatites, U. S. Geological Survey. Also in Cameron, E. N., Jahns, R. H., McNair, A. N., Page, L. R., op. cit.

"replacement." The resulting texture is similar to, but should not be confused with, textures produced by the reaction of hydrothermal (or pneumatolytic) solutions on pre-existing pegmatite during the formation of a *replacement unit*. Fracture-filling units are formed by crystallization of pegmatitic liquid that was injected into fractures across previously formed zones or other units. Replacement units are formed by the action of hydrothermal (or pneumatolytic) solutions on pre-existing pegmatite. These solutions, released from the pegmatitic liquid as a result of local physical or chemical conditions during various stages of crystallization, formed mineral assemblages identical to those found in zones of the same relative age in other pegmatites. Relict textures and structures prove that the pegmatite host rock was essentially solid prior to the formation of the replacement unit.

The recognition of replacement units is essential to sound economic interpretations of pegmatite-mineral deposits, and an understanding of their origin is required. Apparently they have been formed by hydrothermal (or pneumatolytic) solutions, and the very nature of the process precludes prediction of their lateral or vertical extent, except where controlled by a recognizable structural weakness, such as a fracture, gneissoid banding, or wall-rock contact, that could serve as a channelway. Most zonal boundaries are gradational and consequently could not serve as a channelway. In the absence of definite channelways, the resulting unit may be expected to be highly irregular and unpredictable in shape or position.

EVALUATION OF URANIUM DEPOSITS IN PEGMATITE.

At the present time no pegmatite deposits are known in the United States which warrant exploitation for uranium, though many occurrences of uranium minerals in pegmatites have been recorded. Nevertheless, since numerous new discoveries probably will be made by prospectors, it seems desirable that the problem of evaluating them be discussed.

Uranium minerals may be present in all units of any particular pegmatite, but they generally are concentrated in only one or two units. They are rarely evenly distributed throughout any unit. The variation in quantity of a particular mineral from unit to unit, and the uneven distribution of indidivdual grains throughout a unit, has given rise to the impression that the distribution of pegmatite minerals has no uniformity and that the grade and size of the deposit are unpredictable. This, however, is not so because the concentrations of any particular pegmatite mineral are either co-extensive with one or more of the 11 main mineralogic zones listed above or with subdivisions of these zones that have the same structural characteristics as the main zone. Because of their similarity of structure, the prediction of mineral content and lateral or vertical extensions can be made by the same methods.

The variation in the size of the individual accessory minerals, such as uranium minerals, and the low percentages of them in the rock make the evaluation of such deposits more difficult than the evaluation of most metal deposits. The uranium minerals in a single zone may range from microscopic size to masses weighing tens, or even hundreds of pounds, but the over-all content is

normally a fraction of a percent. Because of the nature of the deposits the usual methods of sampling do not yield reliable information about grade, and expensive bulk sampling must be undertaken if a high order of accuracy is necessary. Inasmuch as this type of sampling usually is not warranted and chemical assays which are time consuming and expensive do not always indicate the percentage of the mineral being investigated, more rapid and less expensive methods of determining mineral content are desirable for many purposes. The grade may, of course, be determined if figures on production and the total tonnage of rock mined from a particular unit are available. The mineral content of a zone determined in this fashion will be accurate only if a fair sample of the zone has been mined. How large such a sample must be is determined by the size of individual mineral grains in the zone; if the rock is very coarse grained (crystals over 5 feet in length) the sample must be larger than if the average grain size is only a few inches. In most pegmatite mining operations reliable production figures are not available. The mineral content can be determined, however, by measurement of the exposed area of the mineral sought in any particular zone and, by making a proper correction for differences in specific gravity, this area can be related to the total exposed area of the zone to determine the percentage of that mineral. If the minerals are very fine grained, errors in measurement are, of course, large, and normal sampling procedures are more accurate. Because of the normally wide range in grain size and the uneven distribution of minerals in a zone, all measurements of both the unusually high grade and the barren areas should be included in computing the average grade; otherwise the true potential resources of the deposit may not be recognized. This method of obtaining estimates of mineral content has been used with some success in studies of pegmatite deposits, and where it has been possible to check the results by normal sampling procedures it has been found to be reliable.

The evaluation of pegmatite deposits on the basis of detailed mapping of internal structures and mineral measurements was not used extensively until World War II when the U. S. Geological Survey and the U. S. Bureau of Mines cooperated in underground and diamond-drilling exploration for sheet mica, beryl, and spodumene in pegmatites. The results of this exploratory work, together with subsequent mining, showed that in zoned pegmatites the mineral content and size of the deposits can be evaluated fairly accurately in advance of mining. Although no exploration has been carried out for uranium minerals in pegmatites, the problems of determining reserves are analogous. A few examples are described below to illustrate the degree of accuracy obtainable in predicting the mineral content of pegmatite deposits.

During 1944 and 1945 the U. S. Bureau of Mines explored the Edison spodumene pegmatite, Keystone, S. Dak., by diamond drilling.[11] The exploration program was based on detailed surface and underground mapping by the Geological Survey. Because spodumene was the only lithium mineral present and was both relatively fine grained and fairly evenly distributed through the zones no measurements of crystals were made, and the core,

[11] Clarke, F. F., Zinner, Paul, and others, Edison Spodumene Mine, Pennington County, S. Dak.: U. S. Bur. Mines Rept. Inv. 4234, April, 1948.

sludge, channel, and bulk samples were assayed for Li_2O by the Bureau of Mines. These chemical assays were weighted by zones to determine the grade of five main blocks of ore which have since been partly mined. This subsequent mining, in which 62,000 tons of pegmatite were removed, checked very closely the predicted grade and tonnage. According to the operator's records [12] the Li_2O content was within 5 percent and the tonnage within 10 percent of predictions. Furthermore, the lateral and depth projections of internal units in this structurally complex pegmatite (Fig. 4) were sufficiently accu-

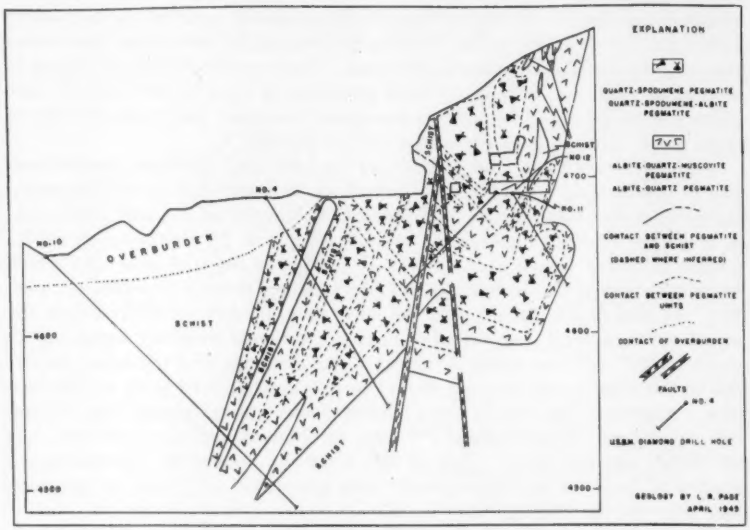

FIG. 4. Cross section, Edison pegmatite, Keystone, S. Dak.

rate to serve as a basis for mining. Additional mapping by the Geological Survey, after some 20,000 tons of ore had been mined, confirmed the original projected positions of spodumene-bearing and barren units within the pegmatite.

In 1947 the Bureau of Mines explored the Hot Shot pegmatite, Custer, S. Dak., for muscovite mica by means of three diamond-drill holes to test predictions made by the Geological Survey as to the extent of a poorly exposed mica zone. Later a shaft was sunk and a crosscut was driven in a vertical plane through one drill hole to test by mining the accuracy of the estimate of mica content in the deposit made from the drill cores.

The results of the drilling showed that the position and shape of the pegmatite and also of the internal units can be predicted within a few feet. Lithia-bearing units were found at depth in their expectable positions, even though

[12] Clarke, F. F., Personal communication.

they did not crop out at the surface. Drilling showed that the mica zones extended vertically as much as 130 feet below the lowest workings and had the normal variation in mineral content from place to place in the zone.

In the hanging-wall part of the zone the three drill holes cut an estimated 4, 12, and 23 percent of muscovite, respectively; the average, weighted according to length of drill core, was 15 percent. The crosscut intersected the hanging-wall mica zone in three places, because of irregularities of the contact, and the footwall mica zone only once. The mica content of the hanging-wall mica zone as determined from the drill cores was checked, first, by determining the weighted average of visually estimated percentages of mica in all areas (125 square feet) of exposure in the crosscut and, second, by measuring the area of mica exposed in 27 square feet of the zone. These methods yielded 16 and 12 percent of mica, respectively. Visual estimates of mica in the footwall zone where cut by the drill hole gave an average of 8 percent, and measurements of areas in the crosscut gave an average of 6.5 percent.

At another mica mine, the Victory, in Custer County, S. Dak. detailed records of production from 1,000 tons of rock in the upper half of two connected pegmatite lenses showed that 5.77 percent of the mica in the wall zone could be recovered by hand methods. One bulk sample of the dump, taken by the Bureau of Mines, indicated that about 16 percent of the rock was mica which was not recovered. Consequently, the over-all mica content was about 22 percent. In two drill cores through the mica zone, 60 feet vertically below the lowest working level, the average muscovite content, weighted according to length of drill core, was about 32 percent. By assuming that the same proportion of this mica would be recovered as in previously mined parts of the mica zone, a reserve of 260 tons of sheet-bearing books was calculated after drilling was completed. Actually about 310 tons, or about 20 percent more than was calculated, was recovered. Part of this error was caused by instituting the practice of hand sorting broken rock twice instead of only once, as had been done prior to the drilling.

During 1943 and 1944 a beryl zone at the Wood Tin mine, Keystone, S. Dak., was mined under a contract with the Metals Reserve Company of the Reconstruction Finance Corporation. The contract was based on the assumption that the beryl content within a single unit was constant for any large tonnage of rock. The beryl content, determined by measuring the area of beryl on 500 square feet of surface exposure, was 1.57 percent; and 1 percent, or about two-thirds of the total quantity of beryl, was estimated by members of the Survey to be recoverable by hand sorting. At the conclusion of the contract about 4,400 tons of the beryl zone had been mined and 40.2 tons, or 0.9 percent, of beryl had been recovered.

These and other similar experiences have convinced the Survey geologists working in the South Dakota area that the extension in depth and mineral content of zones in pegmatites can be predicted on the basis of sound geological studies. If the mineral content and tonnage of lithium minerals, beryl, and sheet-mica deposits can be predicted, it follows that similar methods of study will apply equally well to the uranium minerals because their distribution in pegmatites is similar to that of the other minerals. As new uranium mineral

deposits are found, they should be evaluated in terms of mineralogical and structural units, rather than in terms of the entire pegmatite.

URANIUM DEPOSITS IN DOMESTIC PEGMATITES.

Uranium minerals are known from nearly all of the pegmatite districts in the United States, but in no deposits are they sufficiently abundant to encourage mining. A large number of uranium and rare-earth minerals have been described from domestic pegmatites. Uraninite is the most common and occurs in muscovite-rich units with perthite, quartz, albite, and Li-Mn-Fe phosphates such as lithiophillite-triphylite. Samarskite, euxenite, and monazite

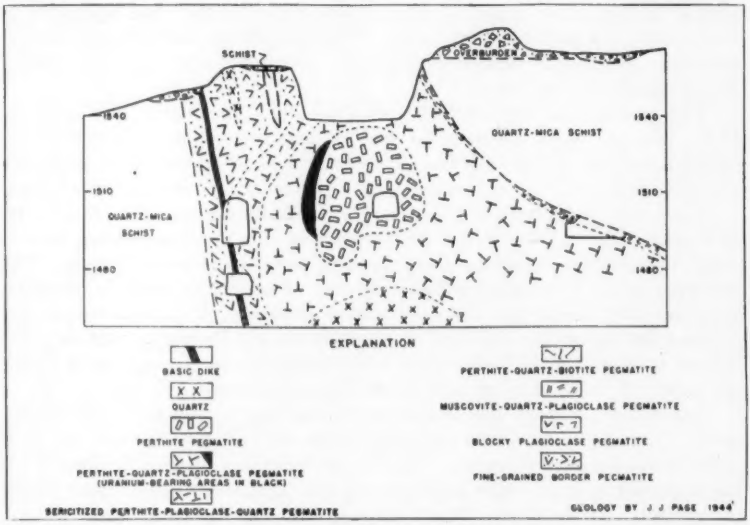

FIG. 5. Cross section, Ruggles pegmatite, Grafton, N. H.

are the only other common uranium minerals. They are most abundant in potash-feldspar-rich units with quartz and albite. Several of the richer uranium pegmatites will be briefly described to show types of occurrences.

The Ruggles mine, Grafton, N. H., has one of the richest concentrations of uranium minerals known in pegmatites of this country. Uraninite crystals and aggregates, associated with secondary alteration products, occur in pod-like areas several feet long in a subdivision of a perthite-quartz-plagioclase zone that surrounds a perthite pegmatite core (Fig. 5). The uranium minerals are mainly on one side of the core in a lenticular unit which is parallel in strike, dip, and plunge to the walls of the core and the containing zone. Uranium minerals also occur in quartz fracture-filling units that cut the perthite-quartz-plagioclase pegmatite.

The Palermo pegmatite, Groton, N. H., contains uraninite and its alteration products in a zone of plagioclase-quartz-muscovite-perthite pegmatite around a central core of quartz-perthite pegmatite (Fig. 6). This zone is continuous and thick on the footwall side, but on the hanging-wall side it occurs as a series of discontinuous lenses. Five places where uranium minerals were observed during mapping are shown on Figure 6; uranium minerals have been removed during mining in other parts of this zone. The uranium-bearing zone, though composed mainly of plagioclase, quartz, muscovite, and perthite, is unusually rich in rare phosphates, beryl, and other minerals.

The Hyatt Beryl pegmatite, Larimer County, Colo. (Fig. 1) has a structure similar to that of the Palermo pegmatite. The uranium-bearing zone consists of discontinuous lenses of quartz-albite-muscovite-perthite pegmatite at the outside of a perthite-quartz core. These lenses contain uraninite and its alteration products associated with quartz, muscovite, albite, perthite, lithiophillite-triphylite, and beryl.

The uraninite at the Bob Ingersoll Dike No. 2 pegmatite, Keystone, S. Dak. (Fig. 3), is in an irregular lens of muscovite-albite (cleavelandite)-quartz pegmatite that lies between a shell-like zone of quartz-albite pegmatite and a hood-shaped zone of perthite-quartz pegmatite. In places it is adjacent to quartz-amblygonite-albite (cleavelandite)-perthite pegmatite and the quartz-spodumene core. Some of the relationships of this uranium-bearing unit to zones suggest that it may be a replacement unit, but proof is lacking. The uraninite occurs as rounded grains, a quarter of an inch or more in diameter, surrounded by orange and yellow alteration products. It is more evenly distributed throughout the unit than in the Palermo and Ruggles mines, and also is finer grained than in these mines, where the grains or aggregates of grains are commonly more than an inch in maximum dimension.

Samarskite, perhaps the second most abundant uranium mineral in domestic deposits, is especially common in the Spruce Pine district, N. C.,[13] Chaffee and Fremont Counties, Colo.,[14] and the Petaca district, N. Mex.[15] It also is present in many other pegmatites of the Appalachian region from Maine to Alabama and the Rocky Mountain region of Colorado and New Mexico. Samarskite is associated with albite and muscovite in zones rich in perthite and quartz. Fluorite, monazite, beryl, and bismuth minerals are common accessory minerals in the Rocky Mountain region.

Euxenite is a fairly common mineral in the pegmatites of the Trout Creek Pass region, Chaffee County, Colo., but it is relatively rare in other pegmatite districts of the United States. It is an accessory mineral associated with the

[13] Maurice, C. S., The pegmatites of the Spruce Pine district, North Carolina: ECON. GEOL., vol. 35, pp. 49–78, 158–187, 1940.

[14] Hanley, J. B., Mineral Resources of Colorado: Colorado Min. Res. Board, Denver, Part II, p. 470, 1947.

Hanley, J. B., Heinrich, E. Wm., and Page, L. R., Pegmatite investigations in Colorado, Wyoming, and Utah: U. S. Geol. Survey Prof. Paper (in preparation), 1949.

Heinrich, E. W., Fluorite-rare earth mineral pegmatites of Chaffee and Fremont counties, Colorado: Am. Mineralogist, vol. 33, pp. 64–76, 1948.

[15] Jahns, R. H., Mica deposits of the Petaca district, Rio Arriba County, N. Mex.: New Mexico Bur. Mines and Min. Res. Bull. 25, pp. 66–67, 98–99, 1946.

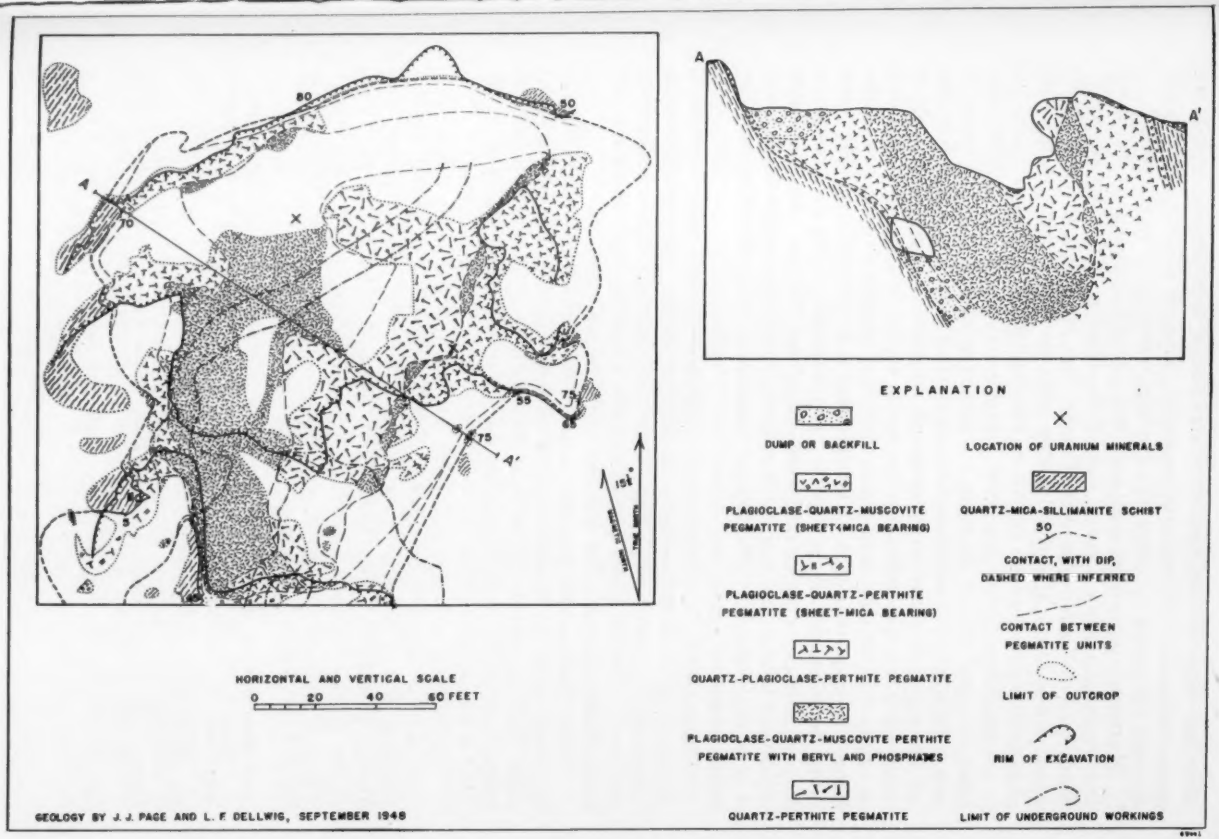

FIG. 6. Map and cross-section, Palermo pegmatite, Groton, N. H.

albite and muscovite that form the matrix around large perthite crystals and quartz masses in perthite-quartz pegmatite. Bismuth minerals, fluorite, and monazite are closely associated with euxenite in most of its occurrences.

Microlite-pyrochlore minerals have been mined for tantalum at the Brown Derby mine, Gunnison County, Colo.,[16] the Harding mine near Dixon, N. Mex.,[17] and the Pidlite mine, Mora County, New Mex.[18] In addition, betafite occurs in the Brown Derby and Pidlite pegmatites. Hatchettolite, a variety of pyrochlore, is a common mineral in the Harding pegmatite.

In the Brown Derby pegmatite, microlite, containing 4.09 percent combined UO_2 and UO_3,[19] occurs in a lepidolite-quartz-cleavelandite pegmatite unit of the core. The microlite grains, as much as a quarter of an inch in size, are not uniformly distributed throughout this unit. The lenticular body or shoot which has been mined was 104 feet in surface length, 3 feet thick, and as much as 60 feet long down dip. Analyses of samples showed the microlite content to range from 0.35 to 1.03 percent; 0.35 percent is probably more nearly representative of the deposit. The remainder of the core contains a very much smaller quantity of this mineral. Small flattened, diamond-shaped crystals of betafite are sparsely distributed in the albite-quartz-biotite wall zone of this pegmatite. The betafite is associated with columbite, monazite, black tourmaline, gahnite, and fluorite.

The occurrence of microlite at the Pidlite mine, Mora County, N. Mex., is similar to that at the Brown Derby in that the microlite is in a lepidolite-albite (cleavelandite)-quartz core (Fig. 2), the outer part of which contains topaz and beryl. Perthite-quartz pegmatite forms a hoodlike body above the core of the Pidlite pegmatite, but is absent on the footwall side.

At the Harding mine microlite occurs in fine-grained lepidolite-rich lenses or masses which are beneath a gently dipping quartz-spodumene pegmatite unit. The hatchettolite occurs most abundantly in another unit, possibly of replacement origin, that is composed essentially of rounded grains of spodumene in a pinkish matrix of microcline, muscovite, albite, and quartz.

The thorium and other rare-earth minerals that commonly contain uranium, such as monazite and allanite, have been observed in several deposits. Monazite is most common in the pegmatite districts of Colorado and New Mexico, particularly in the Trout Creek region of Colorado and the Petaca district of New Mexico. Allanite, accompanied by fergusonite, is not uncommon in Colorado and Wyoming pegmatites and in the Baringer Hill [20] pegmatite of Texas, but is relatively rare in other pegmatite districts.

[16] Hanley, J. B., op. cit., 1947 and 1948.

[17] Jahns, R. H., and Wright, L. A., The Harding beryllium-tantalum-lithium pegmatites, Taos County, N. Mex. (abstract): Econ. Geol., vol. 39, pp. 96–97, 1944.

[18] Jahns, R. H., Lithium-tantalum pegmatites in Mora County, N. Mex. (abstract): Geol. Soc. America Bull. 57, p. 1208, 1946.

[19] Fairchild, J. G., Eckel, E. B., and Lovering, T. S., Microlite from Ohio City, Colorado: Exhibit V, Report of Committee on Geologic Time, National Research Council, April 27, 1935.

[20] Hess, F. L., Minerals of the rare-earth metals at Baringer Hill, Llano County, Texas: U. S. Geol. Survey Bull. 340, p. 290, 1908.

URANIUM DEPOSITS IN FOREIGN PEGMATITES.

Some of the better-known foreign deposits of uranium minerals in pegmatite are described in order to show their similarity to known domestic deposits. An attempt has been made to include all known types of mineral associations, but not all districts will be mentioned among the examples.

In Madagascar,[21] most of the primary uranium ores are in deeply weathered "potassic pegmatites." *Betafite,* the most important ore mineral, is closely associated with biotite at the edges of, or within, smoky quartz-rich zones or masses. Some masses of betafite are cut by crystals of beryl, but usually beryl is rare. Allanite, malacon, uranothorite, and tourmaline are associated with betafite in the larger deposits, but in others euxenite, blomstrandinite (blomstrandine), priorite, tscheffkinite, uranocircite, and uranium-bearing columbite, also may be present. *Euxenite,* the second most abundant uranium mineral, also is present in "potassic pegmatites," always in association with muscovite, beryl, and monazite; and sometimes with columbite, allanite, betafite, samirésite, and uranocircite. Only one occurrence of euxenite was noted in a "soda-lithia pegmatite" and the associated columbite does not contain uranium as does the columbite in the "potassic pegmatites." *Blomstrandinite* associated with columbite and malacon occurs in beryl-bearing "potassic pegmatites" as does *samirésite,* which usually is found with zircon, native bismuth, bismutosphaerite, biotite, and pyromorphite. *Ampangabeite* occurs associated with columbite, monazite, and ilmenorutile in "potassic pegmatites." *Samarskite* is found with fergusonite and uranocircite in the "potassic pegmatites" that do not contain beryl and with yttro-tantalite, garnet, and hematite where beryl is present. *Fergusonite* may also be associated with euxenite, betafite, and tscheffkinite in "potassic pegmatites."

In Africa uranium minerals have been reported from several countries in addition to Madagascar. In Tanganyika [22] uraninite, rutherfordine, monazite, eschynite, samarskite (plumboniobite), and a member of the euxenite group have been found in mica pegmatites on the western side of the Uluguru Mountains and in the western Usambara Mountains. These pegmatites contain quartz, potassic and oligoclase feldspar, and green muscovite with minor ilmenite, biotite, black tourmaline, euclase, apatite, and garnet. Beryl, allanite, monazite, phenacite, galena, bismuthinite, pyrite, chalcopyrite, sphalerite, arsenopyrite, and rutile have also been noted in Tanganyika pegmatites.

In Mozambique [23] pegmatite deposits have been reported that contain samarskite associated with columbite, quartz, mica, feldspar, and tourmaline.

Several uranium minerals have been described in pegmatites of the northwestern part of Cape province, Union of South Africa. Pitchblende asso-

[21] Turner, H. W., Review of the radioactive minerals of Madagascar: Econ. Geol., vol. 23, pp. 62–85, 1928.

Lacroix, A., Minéralogie de Madagascar, Paris, vol. I, 1922, vol. II, 1922, vol. III, 1923.

[22] Williams, G. J., and Skerl, A. F., Mica in Tanganyika Territory: Tanganyika Geol. Div. Bull. No. 14, 47 pp., 7 pls., 1940.

[23] Colin, L. L., Base minerals of Portuguese East Africa: South Africa Min. and Eng. Jour., vol. 54, Part I, pp. 315–317, 1943.

Silva Pinto, A. da, L'importance des gisements de mica dans le district de Mozambique: Cong. Intern. des Mines, de la Mét. et de la Géol. appliquée, VII session, Soc. de Géol. appliquée, vol. 2, pp. 1059–1066, 1936.

ciated with fergusonite, gadolinite, and allanite is reported from the Gordonia area; fergusonite and euxenite from Kenhardt; euxenite, fergusonite, monazite, xenotime, polycrase, gummite, and uranophane from Namaqualand; and euxenite, fergusonite, monazite, and eschynite from Swaziland. Gevers,[24] in his description of Namaqualand deposits that extend into the Gordonia and Kenhardt areas, describes the uranium and rare-earth minerals associated with beryl in microcline-quartz pegmatite. The uranium minerals may also occur at the edge of the quartz masses between feldspar crystals or aggregates, in close association with albite and muscovite. At one mine uranium minerals were found with spodumene. Most of the oxidized uranium minerals were found in "mica greisen" associated with lithiophillite. Euxenite and monazite are mainly in microcline-quartz pegmatite.

In India pitchblende has been produced from the Abriki Pahar mica mine in the Goya district, Bihar province, and samarskite from the Sankara mica mine in the Nellore district.[25] These and other uranium-bearing pegmatites have been noted in other Indian pegmatites.

Uraninite (pitchblende) with its alteration products occurs with beryl, columbite-tantalite, and spodumene in the mica pegmatites of Brazil as part of the potash feldspar-rich units that lie adjacent to quartz cores. Euxenite, polycrase, monazite, and samarskite also have been reported.[26]

The pegmatites of the Hitterö region [27] in Norway contain polycrase-euxenite, blomstrandinite (blomstrandine), and gadolinite associated with allanite and zircon, including malacon. The pegmatite consists of "microcline runite" (graphic granite) in the upper part and "oligoclase runite" in the lower part. In many places these surround a quartz core with microcline on the outside of the core in the upper part and plagioclase in the lower part of the pegmatite. The biotite blades and plates that are associated with the feldspar contain the accessory minerals. Brögger,[28] in describing the pegmatites of Moss, Kragerö, Arendal, and other Norwegian localities, noted the abundance of potassium feldspar and recognized that pegmatites which are dominantly microcline-perthite and quartz, with some biotite, can be divided into two groups. The first group is characterized by an abundance of columbite, samarskite, and monazite; and the second group by the abundance of euxenite-polycrase minerals associated with gadolinite, allanite, yttrotitanite, thorite, and xenotime. Quensel [29] notes the association of uraninite with potash feldspar in the Varutrask pegmatite.

Uranium minerals have been reported from the main feldspar (probably

[24] Gevers, T. W., Partridge, F. C., and Joubert, G. K., The pegmatite area south of the Orange River in Namaqualand: Union of South Africa, Dept. of Mines, Geol. Survey, mem. 31, pp. 41–56, 82, 105–109, 1937.

[25] Chowdbury, R. R., Handbook of Mica, p. 272, Calcutta, 1939.

[26] Johnston, W. D., Jr., Beryl-tantalite pegmatites of northeast Brazil: Geol. Soc. America Bull., vol. 56, p. 1038, 1945.

[27] Anderson, Olge J., The granite pegmatites of Hitterö, southwestern Norway: Geol. Foren. Förhand., Bd. 64, H. 2, No. 429, pp. 97–116, 1942.

[28] Brögger, W. C., Die Mineralien der südnorwegischen Granit pegmatite gänge: Vid. Selsk. Ski. Math-Naturv. Klasse, 1906.

[29] Quensel, P., Minerals of the Varutrask pegmatite. XIX—The uraninite minerals (ulrichite and pitchblende): Geol. Foren. Förhandl., vol. 62, p. 391, 1940.

potash) districts of Russia.[30] Labuntzov's maps show internal structural units identical to those described in this country as zones.

According to Ellsworth[31] the typical Canadian pegmatites that carry uraninite are exceptionally rich in quartz, which is segregated into large masses, and many of them have considerable muscovite, commonly accompanied by biotite, in a type of deposit normally prospected for mica. In these deposits the feldspar is generally microcline, but in most some plagioclase is present. Quartz may be more abundant than feldspar. Several contain the unusual carbonaceous rare-element material thucholite associated with uraninite and zircon (including cyrtolite). Samarskite, allanite, or other rare-earth minerals also may occur in the same deposit.

The euxenite pegmatites are less common than the uraninite type of uranium pegmatites in Canada, especially in the southern part of the shield in Ontario. These are the type of pegmatite usually prospected for potash feldspar, which contain crystals or masses of feldspar separated by massive quartz. The feldspar is usually mirocline, though some perthite may be present, and a narrow band rich in plagioclase feldspar may be present at the wall-rock contact. Euxenite is associated with allanite and columbite-tantalite. Ellsworth includes the "calcite granite pegmatites" of north Hastings County, Ontario, as well as the "calcite-fluorite-apatite vein dykes" of Haliburton with his uraninite and euxenite pegmatites.

In summary, the uranium minerals in foreign pegmatites, as well as in the United States, appear to be most common in those bodies that contain an abundance of potash feldspar. Uraninite shows a close association with muscovite and biotite; betafite and allanite with biotite; euxenite and monazite with beryl and in a few deposits with muscovite; and samarskite with columbite and fergusonite. Minor amounts of uranium minerals associated with lithium minerals have been noted. Nearly all of the uranium minerals are associated with some albite, but albite is rarely the dominant feldspar.

PROSPECTING FOR URANIUM IN PEGMATITES.

It is apparent from descriptions of both domestic and foreign deposits that pegmatites could not be considered as a major source of uranium even if chemical methods were available for its recovery from the complex minerals in which it occurs. The appreciable production from Madagascar, however, is sufficient to indicate that commercial, but small, deposits might be found; therefore, although prospecting in the pegmatites is not expected to be lucrative, it might be desirable to point out the known geological relationships that might serve as guides in finding new deposits.

[30] Fersman, A. E., Granite pegmatites, Vol. I: Akad. Nouk, U.S.S.R. Moscow-Leningrad 712 pp., 1940.

Labuntzov, A. N., Pegmatites of Northern Karelia and their minerals: Akademiya Nouk, U.S.S.R., Moscow-Leningrad, Institut Geologisheskikh Nouk, Pegmatites of the U.S.S.R., vol. II, 260 pp., 1939.

[31] Ellsworth, A. V., Rare element minerals of Canada: Canada Dept. of Mines, Geol. Survey, Econ. Geol. series No. 11, pp. 119–120, 1932.

1. Uraninite and the multiple oxides of uranium, columbium, tantalum, and titanium, together with their alteration products, occur in perthite-rich zones of pegmatites.

2. Uraninite is most likely to occur in the muscovite-rich part of perthite-rich intermediate zones, especially if the muscovite is accompanied by albite intergrown with quartz. Scrap mica is more likely to be produced from this type of deposit than sheet mica.

3. The euxenite-polycrase group is most common in perthite-rich zones of pegmatites in which large crystals of perthite are surrounded by massive quartz. Beryl, bismuth minerals, and fluorite associated with albite and muscovite at the edges of the quartz are favorable indications of its presence.

4. The microlite-pyrochlore group of minerals is most abundant in lepidolite-rich or spodumene-rich zones.

5. Samarskite and monazite are most likely to occur in perthite-plagioclase-quartz zones, and may be concentrated in that part of the zone richest in muscovite.

6. Golden beryl, dark smoky to black quartz, and reddish-brown stained feldspar or muscovite are indications of the presence of uranium-bearing or other radio-active minerals.

7. Allanite and betafite are commonly associated with biotite-rich perthite-plagioclase-quartz zones or pegmatites.

8. In Madagascar, betafite is closely associated with biotite in potash-rich pegmatites, but occurrences in the United States are all in lithium-bearing pegamtites.

In summary, potash-rich (perthite-rich) zones or pegmatites are the most likely sources of uranium minerals and soda-rich (albite-rich) or lithia-rich (lepidolite-rich) zones or pegmatites are somewhat less favorable. Furthermore, sheet-mica-bearing pegmatites are less favorable than the scrap-mica-bearing deposits. Uranium minerals from pegmatites probably will continue to be a byproduct of mining for other minerals, and appreciable production can not be expected from this source.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Aug. 18, 1949.

CHARACTERISTICS OF MARINE URANIUM-BEARING SEDIMENTARY ROCKS.[1]

V. E. McKELVEY AND JOHN M. NELSON.

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ABSTRACT.

Many marine sedimentary black shale and phosphorite formations contain 0.01 to 0.02 percent uranium, and one, the alum shale of Sweden, contains as much as 0.5 percent. The published fact that uranium is already being recovered on a laboratory scale from Swedish deposits forcefully suggests that similar deposits in the United States and possibly many other countries may prove to be an important future source of uranium.

The marine uranium-bearing black shales are rich in organic matter and sulfides and contain little or no carbonate. The best are found in relatively thin formations of pre-Mesozoic age. The nature of the uranium-bearing mineral or compound is not known. In contrast, nonmarine black shales, as a group, are not uraniferous.

All marine phosphorites tested thus far are uraniferous and so too are the phosphatic nodules found in many marine black shales. With some exceptions, the uranium increases in a general way with increase in phosphate content and is believed to be in the phosphate mineral. Like the black shales, the phosphorite formations are characteristically thin; many

[1] Published by permission of the Director, U. S. Geological Survey, and presented before the Society of Economic Geologists, San Francisco, February 1949. All information in this paper relative to foreign occurrences of uranium has been obtained solely from material already published.

are associated with unconformities or, in other words, periods during which little else in the way of sediment accumulated.

Significant concentrations of uranium in marine sediments other than black shales and phosphorites are thus far known only in beach placer deposits and the gold-bearing conglomerates of the Witwatersrand district, South Africa.

Uranium may be found in other types of marine sediments on further prospecting, but especially promising are the sediments rich in organic matter, phosphate, or both, found in relatively thin formations believed to be the entire depositional products of long periods of geologic time. Such formations are most characteristic of those areas where, at the time of deposition, the adjacent land masses were so stable and low that the influx of clastic materials was small; the basin of deposition was large or of such configuration that fine-grained sediments could accumulate; and chemical conditions in the seawater prevented deposition of large amounts of carbonate.

INTRODUCTION.

RECENT reports[2] that Sweden and possibly Russia are recovering uranium from marine oil shales forcefully demonstrate that some marine sedimentary rocks are important sources of uranium. Uraniferous deposits similar to those of Sweden and Russia are found in the United States, and published reports indicate, moreover, that such deposits are to be found in many countries, both large and small, over the world.

These deposits are large but low grade. Shales of the type Sweden and Russia are developing generally contain only 0.01 to 0.02 percent uranium (one pound of uranium in 2.5 to 5 tons of rock), though some portions of the Swedish shales contain as much as 0.5 percent.[3] The small demand for uranium in pre-war years, when uranium was used principally as a coloring agent and as a source of radium, was met by mining small tonnages of much higher grade ore, containing 2 to 50 percent uranium. Although some of the low-grade sedimentary deposits were known for many years, they were never seriously considered as a source of uranium. In the future, however, these low-grade sediments may well be the principal source of uranium and a source within the reach of many nations not previously believed to possess important uranium reserves.

Whether this widespread distribution of recoverable uranium is to be regarded as frightening or comforting, it is plain that we must quickly appraise our own uranium reserves. Because this task is a large one, and because our nation depends upon private industry to exploit our mineral resources, the Atomic Energy Commission recently invited the mining industry to aid in

[2] Uranium ore reported discovered in Sweden: The Times Herald, Washington, D. C., November 17, 1948. Uranium from Estonian oil shales: Cincinnati Enquirer, Cincinnati, Ohio, July 20, 1948.

[3] Nordenskiold, A. E., Remarques sur le fer natif d'ovifak et sur le bitume des roches cristallines de Suède: Acad. sci. Paris Comptes rendus, vol. 116, pp. 677–678, Paris, 1893.

Landin, John, Radium i Sverige: Arkiv fur Kemi, Mineralogi, och Geologi, K. svenska vetensk. akad Handl., vol. 2, no. 2, pp. 1–7, Jan. 1905.

Eklund, Josef, Atomic energy and economic progress: Skandinaviska Banken Aktiebolaget Quarterly Review, vol. 28, no. 1, pp. 5–9, 1947.

Orlov, N. A., and Kurbatov, L. M., The radioactivity of bituminous shale: Khimiia Tverdogo Topliva, vol. 5, pp. 525–527, 1934; vol. 6, pp. 288–291, 1935; vol. 7, pp. 94–98, 1936.

the discovery and development of uranium deposits [4] and suggested that the U. S. Geological Survey help stimulate such activity by summarizing general information on the occurrence of uranium in marine sedimentary rocks. This the present paper attempts in preliminary fashion only; it is hoped that a more thorough treatment of the subject will be presented later as more data are accumulated and interpreted.

OCCURRENCE OF URANIUM IN MARINE SEDIMENTARY ROCKS.

The uranium content of the earth's crust has been estimated at 0.0002, 0.0004, and 0.0009 percent by Anderson, Goldschmidt, and Fersman,[5] respectively. It is not surprising that certain rocks of marine origin contain 0.01 to 0.02 percent uranium, for such a concentration is only 10 to 50 times that found in the earth's crust. Sedimentary iron, phosphate, and manganese-bearing formations commonly contain concentrations of iron, phosphorus, and manganese of 9, 100, and 500 times, respectively, the average amounts found in the earth's crust.

Such concentrations are found in several classes of marine sediments, including beach placers and conglomerates, but most of the known uranium-bearing marine rocks are of two principal types: black shale and phosphorite.

Uranium-Bearing Black Shale.

Uranium in black shale was first discovered in Sweden in 1893 in the alum shale of Cambrian age.[6, 7] Since then uranium has been found in black shales of several other formations, including the *Dictyonema* and Leningrad shales in Estonia and Russia,[8] which are the stratigraphic correlatives of the alum shale of Sweden; the Devonian and Mississippian Chattanooga shale of east-central

[4] Gustafson, J. K., Atomic energy and the mining business: an invitation. Remarks presented before the American Mining Congress at San Francisco on September 23, 1948.

[5] Anderson, J. S., Chemistry of the earth: Royal Soc. New South Wales Jour. and Proc., vol. 76, pp. 329–345, 1942. Goldschmidt, V. M., Geochemische Verteilungsgesetze der Elemente (IX), Die Mengenverhältnisse der Elemente und der Atom-arten: Skrifter det Norske Videnskaps-Akademii, Mat. Nat. Klasse no. 4, pp. 58–62, Oslo, 1937. Fersman, A. E., Geochimiya: Leningrad, 1932.

[6] Most of the publications listed below contain radium or uranium analyses. Assuming radium and uranium are in equilibrium, radium, which is generally reported in units of 10^{-12} gram of radium per gram of rock, can be converted to percent uranium by multiplying by a factor of approximately 3×10^{5}. Most of the published determinations are not reliable because of the inaccuracy of early analytical methods.

[7] Nordenskiold, A. E., op. cit.

Winkler, Clemens, Zur Zusammensetzung des Eisens von Ovifak in Grönland und der bituminösen Kohle (des Kolms) aus der cambrischen Formation Westergötlands: Zeitschr. Kristallographie und Mineralogi, vol. 37, pp. 286–288, Leipzig, 1903.

Landin, John, op. cit.

Holmberg, B., and Unnerstad, A. J., Destillationsforsok med bituminosa avlagringar from Billingen; Forsok med Billengens kolm: Ingeniörs Vetenskaps Akademien, Handlingar no. 16, pp. 71–78, Stockholm, Sept. 1922.

Wells, R. C., Stevens, R. E., Further studies of kolm: Wash. Acad. Sci. Jour., vol. 21, pp. 409–414, 1931.

Eklund, Josef, op. cit.

Cadman, W. H., The oil shale deposits of the world and recent developments in their exploitation and utilization, reviewed to May 1947: Inst. of Petroleum Jour., vol. 34, no. 290, pp. 109–132, London, 1948.

[8] Orlov, N. A., and Kurbatov, L. M., op. cit.

United States;[9] the Woodford chert of Oklahoma, which is a partial stratigraphic equivalent of the Chattanooga; the Precambrian Nonesuch shale of Michigan;[10] and the Mississippian Calico Bluff formation of east-central Alaska.

It should be emphasized that by no means all marine bituminous or carbonaceous rocks are appreciably uraniferous. The Silurian black shales of Maine and the Miocene asphaltic sands of California, for example, are not abnormally radioactive. The nonmarine oil shales, coals, and associated black shales, and asphaltites as a group have an abnormally low uranium content; in fact, according to Russell,[11] they are among the least radioactive of all rocks.

The uranium-bearing marine shales resemble one another in many ways: all are black or dark in color, rich in organic matter and sulfides, low in carbonate, relatively thin, and those known are of pre-Mesozoic age.

All the highly uraniferous marine shales contain large amounts of organic matter and it appears that, within a given formation at least, the most uranium is found in those rocks containing the most organic matter. For example, many layers of both the alum shale of Sweden and the Chattanooga shale contain uranium, but the highest concentrations in the alum shale are found in nodules and lenses of nearly pure bitumen, called "kolm"; and in the Chattanooga the most highly uraniferous beds are extremely thin layers of almost pure bitumen. Beers[12] has shown that in the Sunbury and Antrim shales, which are partial correlatives of the Chattanooga shale, the uranium content increases directly with increasing percentage of carbon. The uranium-organic matter ratio differs in each of the uranium-bearing formations known, however, and, indeed may be found to differ from place to place in the same formation.

Another striking characteristic of the uraniferous shales is that they are thin as compared with other formations of similar age. Thus the Chattanooga shale is only 5 to 100 feet thick over much of its extent and yet it is the entire product of sedimentation during much of late Devonian and early Mississippian time. Although the uranium content decreases from Tennessee northward to Michigan as the thickness of formations of similar age increases, Russell[13] believes that the uranium content in the same formation increases as the thickness increases westward, and Glebov[14] reports that the thicker the series of *Dictyonema* shales in Estonia, the greater is the radioactivity of separate layers. These observations of the relation of the uranium content to thickness within a given formation are not necessarily discordant in meaning.

[9] Russell, W. L., The total gamma ray activity of sedimentary rocks as indicated by Geiger counter determinations: Geophysics, vol. 9, no. 2, pp. 197, 209, 1944.

Beers, R. F., and Goodman, Clark, Distribution of radioactivity in ancient sediments: Geol. Soc. America Bull., vol. 55, p. 1243, 1944.

[10] Holmes, Arthur, Physics of the earth, Part IV, The age of the earth: National Research Council, Bull. 80, p. 267, 1931.

[11] Russell, W. L., Relation of radioactivity, organic content, and sedimentation: Am. Assoc. Petroleum Geologists Bull., vol. 29, p. 1480, 1945.

[12] Beers, R. F., Radioactivity and organic content of some Paleozoic shales: Am. Assoc. Petroleum Geologists Bull., vol. 29, p. 11, 1945.

[13] Russell, W. L., op. cit., p. 1489, 1945.

[14] Glebov, S. M., Radioaktivnost diktionemovykh slantzer: Leningradski Gornyi Institut, Leningrad, Zapiski, vol. 14, pp. 1–12, 1941.

If the increased thickness is caused by relative increase in amount of uranium-bearing substances, organic matter for example, the uranium content would, of course, increase too; if on the other hand, the increased thickness were caused by relative increase of non-uranium-bearing materials, detritus, for example, the relative uranium content would decrease because of dilution. Whether or not the uranium content increases or decreases with increasing thickness in a given formation, the fact remains that uranium-bearing shales are thin compared to other formations that represent the deposition product of similar periods of time.

All the uraniferous black shales listed here are of the bituminous type from which oil may be distilled, rather than the carbonaceous or coaly type. Lesser concentrations of uranium are known in some marine carbonaceous shales, such as the ampelite of France,[15] and more exploration may show that certain carbonaceous shales contain amounts as great as those found in the bituminous ones.

Thin lenses, nodules, or disseminated particles of pyrite or marcasite are found in all the uranium-bearing black shale formations. In the Chattanooga shale, at least, the uranium does not occur in the sulfides and although the amount of uranium in many places increases as the amount of sulfide increases, this relation is by no means a consistent one.

The known uranium-bearing black shales contain little or no calcium or magnesium carbonates. This relation is especially striking in the Chattanooga shale, where the uranium content is much less in rocks containing only slight quantities of carbonates than in rocks containing no carbonates.

As mentioned by Russell,[16] older shales appear to contain more uranium than the younger shales. No post-Paleozoic marine shales known to us contain as much as 0.01 percent uranium; in contrast, the most uraniferous shale known is the Cambrian alum shale of Sweden. This observation is of course based on limited data and may be disproved on further exploration.

Mineralogy.—Most of the uranium in the black shale is in an acid-soluble form and seems to be in the fine-grained fraction of the rock. Beyond that, nothing is known as to its mineralogy. No uranium-bearing mineral has yet been identified or seen, even on microscopic examination. In fact, it is possible that no distinct uranium-bearing mineral is present in many of the shales, for the uranium may be in an organic compound or the uranium ion may be held by ion exchange, or by adsorption on organic matter or clay minerals, or as impurities in the crystal lattice of common minerals.

The wide association of uranium with organic matter, as well as the fact that the most uraniferous portions of the shales (such as the kolm of the Swedish shales and the bituminous layers of the Chattanooga) consist of nearly pure bitumen, suggest that the uranium is held by organic matter, though this has not yet been positively demonstrated. Organic compounds of uranium are known, but none have been identified in nature, as far as known. Nevertheless, some organic compounds capable of forming chelate rings, in

[15] Muchemblé, G., Sur la radioactivité élevée des roches marines du terrain houiller du nord de la France: Acad. Sci. Paris Comptes rendus, vol. 216, pp. 270–271, 1943.
[16] Russell, W. L., op. cit., p. 1486.

which certain metals can be held as part of the compound, may occur in nature,[17] and uranium may occur in one or more of them. Uranium, in some occurrences, may be adsorbed by organic matter. Fredrickson [18] points out that "all forms of so-called amorphous carbon, from lampblack and coke to charcoal, are graphitic in character." It is therefore layered in structure and, "because of its structure, with its extensive internal surfaces and unsatisfied valencies, charcoal (and similar forms of carbon) possesses the property of adsorbing ions to a remarkable extent." Fredrickson thinks it possible that the UO_2^{++} ion, which consists of two oxygen atoms located at opposite sides of the uranium atom, "is adsorbed between the graphite layers of carbonaceous material, forming a strong structure due to the stable UO_2^{++} ion holding the two layers together." Though there is not always a direct or constant relation between the amount of uranium and the amount of organic matter present, this is not proof that the uranium does not occur in the organic fraction or in an organic compound; even if it is held in the organic matter by ion exchange or adsorption, it is probably in a particular kind of organic matter, the amount of which may bear no relation to the total amount of organic matter present.

It seems clear that uranium can also be attached to clay minerals and other minerals possessing a high adsorptive power. Uranium is reported, if only in small amounts, in non-carbonaceous clays [19] and gibbsite; [20] Beers [21] reports experiments showing that certain clay minerals adsorb large amounts of uranium. Whether or not such minerals contain an appreciable portion of the uranium in black shales is not known, but the facts that no non-carbonaceous shales or clays are known to contain important amounts of uranium, and that the most uranium is found in bituminous layers or nodules that contain only small amounts of inorganic material, suggest that the uranium in the black shales is more likely attached to organic matter than to clay.

Uranium-bearing Phosphorites.

Uranium in phosphorite was first discovered in 1924 in the phosphorite of Cretaceous and Eocene age in Algeria.[22] Significant concentrations of uranium or radioactive substances have since been reported in other phosphorites of the same general age in Egypt, Tunisia, and Morocco; in the Cretaceous phosphorites of the Ivota River region and the Tertiary phosphorites of the Volsk region of Russia;[23] the Permian Phosphoria formation of the Northwestern States; and the Pliocene Bone Valley formation of Florida. Uranium is found too in phosphatic nodules in many black shales, such as those of Pennsylvanian age at the top of the Checkerboard limestone member of the Coffey-

17 Suggested by H. W. Lakin, U. S. Geological Survey.

18 Fredrickson, A. F., Some mechanisms for the fixation of uranium in certain sediments: Science, vol. 108, p. 184, 1948.

19 Russell, W. L., op. cit., pp. 1472–1478, 1945.

20 Fredrickson, A. F., op. cit.

21 Beers, R. F., op. cit., p. 15, 1945.

22 Hébert, Claude, Contribution á l'étude de la chimie des phosphates de calcium: Annales des mines, Memoirs, vol. 136, no. 4, pp. 5–93, Paris, 1947.

23 Rusakov, V. P., O Soderzhanii Radiya i Toriya v Fosforitakh: Akad. Nauk U.S.S.R., Leningrad-Moscow, Doklady, Series A, no. 3, pp. 25–33, 1933.

ville formation and of the Fort Scott (Hayworth and Scott's Oswego) limestone of Oklahoma;[24] the top of Moore's Bourbon formation and in his Hushpuckney and Stark shales of Kansas. The small number of determinations available on the residual deposits, such as those of Tennessee and Florida (the "hardrock" phosphate), and the phosphatized limestone deposits of the Pacific Islands, suggests that they do not contain significant amounts of uranium.

All marine phosphate formations thus far tested contain significant amounts of uranium. Unlike the black shales, the uranium-bearing phosphorites range in age from Paleozoic to Cenozoic, and the older phosphorites do not appear to be more uraniferous than the younger ones. In a general way, the uranium content of the phosphorites increases as the phosphate content increases. A high-grade phosphate rock in one formation is likely to contain about as much uranium as does the same quality phosphate in another formation. Exceptions to this generalization are numerous, however, at least in the phosphorites of this country. Certain high-grade phosphate beds in the Phosphoria formation, for example, contain only small amounts of uranium, and the most uraniferous beds yet discovered in both the Phosphoria and Bone Valley formations are not the most phosphatic.

In the phosphorites of the Phosphoria formation a strongly negative relationship exists between uranium and carbonate CO_2. Of the samples tested thus far, few containing more than 0.005 percent uranium contain more than about 2 percent carbonate CO_2, and none containing more than 0.01 percent U contain more than 2 percent carbonate CO_2.

In the Pliocene Bone Valley formation, according to MacNeil,[25] available analyses suggest that the uranium content of the phosphorites is greater in those having a clay-sized matrix than in those which have a sandy matrix; the most uraniferous layer found thus far is a non-carbonaceous, weakly phosphatic clay.

The phosphorites, like the uraniferous black shales, are characteristically thin formations and many are associated with unconformities [26] or, in other words, they were concentrated in periods during which little else in the way of sediment accumulated. Thus the Phosphoria formation, which represents half, and perhaps even all, of Permian time, is only 200 to 500 feet thick over most of its extent and is the time equivalent of 3,000 to 5,000 feet of sediments in the Permian of Texas.[27] As in the shales, the uranium content of the beds may increase or decrease as the thickness of a given formation increases, depending upon whether or not the uranium-bearing materials cause the increase in thickness or are diluted by increased amounts of non-uraniferous materials. For example, the uranium content of the Phosphoria formation increases westward from Wyoming into Idaho where the increase in total amount of

[24] Russell, W. L., op. cit., pp. 205, 208, 1944.

[25] MacNeil, F. Stearns, U. S. Geological Survey, personal communication.

[26] Goldman, M. I., Basal glauconite and phosphate beds: Science, new ser., vol. 56, pp. 171–173, 1922. Pettijohn, F. J., Intraformational phosphate pebbles of the Twin City Ordovician: Jour. Geology, vol. 24, p. 373, 1926.

[27] McKelvey, V. E., Stratigraphy of the phosphatic shale member of the Phosphoria formation in western Wyoming, southeastern Idaho, and northern Utah: U. S. Geol. Survey, open file report, 1946.

phosphate causes a marked increase in thickness of the whole formation; to the west in Montana, however, the same westerly increase in total phosphate is accompanied by an even greater increase in non-phosphatic sediments, so the phosphatic and uraniferous beds are of lower quality.

All phosphorites contain various amounts of one or more impurities—principally clay and other fine detritus, but also carbonate, organic matter, chert, and glauconite. The Phosphoria formation contains various amounts of phosphate, fine-grained clastics, organic matter, carbonates, and chert; although many layers are composed mainly of one of these materials, no layer is composed of one alone; every phosphate bed contains some clay and many contain some organic matter or carbonate. The Bone Valley formation (which in part was derived by the erosion and reworking of the underlying, less phosphatic Miocene Hawthorn formation) contains much clay and sand but little or no organic matter and very little carbonate; most of the carbonate, according to MacNeil, consists of fragments of partly phosphatized limestone. Incidentally, the phosphate of the Bone Valley formation seems to be more uraniferous than the phosphate in the Hawthorn formation, from which it was derived.

The phosphatic black shales, such as those of Pennsylvanian age in Kansas and Oklahoma, are a cross between the typical phosphorite deposits and the uraniferous black shales. Some of them contain uranium in the non-phosphatic shale layers, even at places where the phosphatic nodules are absent; but the nodules, where present, generally contain more uranium than the enclosing shale.

Mineralogy.—Most of the uranium in the phosphorites seems to be in the phosphate mineral, which is a fluorapatite. This is shown by the general relation between uranium and phosphate and, more convincingly, by the fact that the amount of uranium dissolved on acid treatment is proportional to the amount of phosphorite dissolved. The nature of the occurrence in the fluorapatite is unknown but it is possible that the uranium proxies for calcium (which has about the same ionic radius) in the crystal structure. The previously mentioned relation of uranium to the argillaceous phosphorite and its concentration in the weakly phosphatic clay in the Bone Valley formation suggest that some of the uranium there may be in or attached to clay minerals. The lack of a constant uranium-phosphate ratio in the phosphorites of both the Phosphoria and Bone Valley formations may be due to the fact that most of them generally contain clay or organic matter, either or both of which might contain some uranium; more likely however, the inconstancy of the ratio in most phosphorites is a simple expression of the amount of uranium available at the time of deposition.

Miscellaneous Uraniferous Marine Sediments.

Significant concentrations of uranium in marine sediments other than black shales and phosphorites are thus far known only in the gold-bearing

Precambrian or Cambrian conglomerates of the Witwatersrand,[28] South Africa, and beach placer deposits.

The origin of the South African Rand conglomerate is a perennial enigma. No agreement has been reached as to whether the conglomerate is marine or nonmarine or whether the gold is placer or hydrothermal.[29] The mineralized layers are thin, but are remarkably continuous over great distances along the strike as well as down the dip of the beds. The extreme regularity and continuity of the mineralized beds have suggested that the formation and its metals are of marine origin, but conclusive evidence is admittedly lacking. At least some, if not all, the uranium occurs as uraninite.[30]

Most radioactive beach placers are high in thorium rather than uranium, but the beach placers at Nome, Alaska, are uraniferous as well. Both zircon and monazite, which are found in many sandstones and placer deposits, sometimes carry uranium, but detrital uranium minerals such as pitchblende and uraninite are not common in heavy-mineral suites from sandstones. This fact suggests that most primary uranium minerals disintegrate or decompose on weathering and are not likely to be concentrated in marine placer deposits.

Similar Characteristics of Uraniferous Sediments.

The similarities in occurrence of the uraniferous sediments of the different types described bear repetition. All are of marine deposition, and their nonmarine counterparts, except the placers, are weakly uraniferous. All are relatively thin formations when compared to other formations deposited during the same time interval. Most of the uranium-bearing layers, as well as other associated beds, have great lateral continuity both in thickness and composition. Most of the uraniferous beds are composed of fine-grained rocks in which coarse clastics are absent, and fine clastics, carbonates, and other chemical precipitates except phosphates and sulfides are absent or are relatively minor constituents. All are associated with organic matter, phosphate, or both.

ORIGIN.

The uranium in the marine sediments of the type described is of syngenetic origin—that is, it was deposited at the same time as the containing sediments. This is shown by the fact that thin uraniferous layers persist over areas of thousands of square miles with little if any change in lithology or uranium content and are interstratified with layers having markedly different composition, both as regards major and minor constituents. Moreover, the uranium-bearing rocks are as diverse in texture, permeability, and porosity as many of the non-uraniferous rocks with which they are interbedded.

[28] Archambault, G. H., South Africa announces rich uranium find: New York Times, New York City, N. Y., January 17, 1947.

[29] Lindgren, W., Mineral deposits, pp. 240–246, McGraw-Hill Book Company, New York, 1933.

[30] Bateman, A. M., Economic mineral deposits, p. 443, John Wiley and Sons, Inc., New York, 1942.

Source of Uranium.

As uranium occurs in sea water today (about 0.000002 gram per liter) [31] and is found in acid-soluble form in the sediments, it seems clear that the immediate source of the uranium was the sea water itself, and that the ultimate source was the land areas. Both Goldschmidt [32] and Russell [33] have shown by different lines of evidence that nearly all the uranium that could have been eroded from the lands during all of geologic time is in the sediments, rather than in the sea water. But the manner of its precipitation and deposition and the factors leading to its concentration in the sediments can only be conjectured.

Manner of Precipitation of Uranium.

Uranium may have been removed from sea water and deposited in the sediments in at least two general ways: (1) direct precipitation as an inorganic uranium salt, and (2) selective removal by organisms or by substances for which it has an affinity. These methods are not listed in order of likelihood of their operation. It is possible, if not probable, that uranium was removed from the sea water and fixed in the sediments in several ways.

Direct Precipitation as a Uranium Salt.—Direct precipitation would result only if the sea water were saturated with a uranium salt. If the sea water is saturated with one or more uranium salts now, and this basic fact is simply not known to us, it is reasonable to suppose that it might have been saturated during much of geologic time. If so, uranium would have been precipitated from the sea about as fast as it came from the lands, and most of the uranium would be found, as is true, in sediments instead of the sea. Nearly all marine sediments therefore would contain some uranium, and those that contained the least amount of diluting materials [34]—not only the black shales and phosphorites, but deep sea sediments as well—would contain the most uranium. Although the shales and phosphorites are appreciably uraniferous, the deep sea sediments tested for uranium contain only about 0.0005 to 0.001 percent—an amount not nearly sufficient to account for their radium content.[35] In fact, Piggot and Urry [36] have been led to the conclusion that "the ocean is a reservoir for most of the uranium that is poured into it, while the ocean bottom is the repository for the transient radium." As previously mentioned, both Goldschmidt and Russell have shown that most of the uranium that has been brought to the sea is in the sediments rather than the sea water, but it

[31] Föyn, E., Karlik, B., Petterson, H., and Rona, E., Radioactivity of sea waters: Nature, vol. 143, no. 3616, pp. 275–276, 1939; also in M. Goteborgs Kungl. Vetenskaps-och Vitterhets-Samhälles Handlinger, Ser. B., vol. 6, pp. 1–44, 1939.

[32] Goldschmidt, V. M., The principles of distribution of chemical elements in minerals and rocks: Chem. Soc. Jour., pp. 655–673, 1937. See also Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., The Oceans, pp. 220–222, Prentice Hall, New York, 1942.

[33] Russell, W. L., op. cit., p. 1483, 1945.

[34] Weaver, Paul, A theory of the distribution of radioactivity in marine sedimentary rocks: Geophysics, vol. 7, no. 2, pp. 192–198, 1942.

[35] Urry, W. D., The radioactive determination of small amounts of uranium: Am. Jour. Sci., vol. 239, p. 203, 1941.

[36] Piggot, C. S., and Urry, W. D., Radioactive relations in ocean water and bottom sediment: Am. Jour. Sci., vol. 239, p. 85, 1941.

seems plain from Piggot and Urry's work that the whole ocean is not saturated with uranium, and that if uranium is being concentrated in any marine sediments today, it is being concentrated for reasons other than the mere lack of diluting materials.

If, as seems probable, the sea is not now and never has been saturated with uranium salts, the uranium brought from the lands must have been selectively removed from the sea before it reached the saturation point. This might have happened in one or all of the following ways: (a) utilization by organisms; (b) adsorption by clays or other colloidal matter; or (c) fixation or complexing by various chemical compounds.

Precipitation of Uranium by Organisms.—The strong relation between uranium and organic matter in the black shales suggests that organisms in some way may have been instrumental in removing uranium from the sea water and concentrating it in the shales. Some organisms are known to concentrate certain metals—vanadium, copper, and radium are familiar examples [37]—and to take certain elements from the solution available to them, even if the solution is not saturated with inorganic compounds of those elements. Although the uranium content of marine organisms is not known, some animals are known to remove uranium from the bloodstream and concentrate it in the body tissue and bone.[38] Some elements or compounds thus precipitated are taken back into solution on the death and decay of the organism if the solution is not saturated with that particular substance, as is the case in the phosphate, nitrogen, and sulfur cycles in the sea today.[39] But this process occurs only if the compound is soluble—if the organism has succeeded in complexing or fixing the uranium ion in some relatively insoluble compound, either organic or inorganic, it would not go back into solution on death of the organism unless the composition of the solution changed markedly.

[37] Phillips, A. H., A possible source of vanadium in sedimentary rocks: Am. Jour. Sci., 4th ser., vol. 46, pp. 473–475, 1918. Marks, G. W., The copper content and copper tolerance of some species of mollusks of the Southern California coast: Biol. Bull., vol. 75, pp. 224–237, 1938. Evans, R. D., Kip, A. F., and Moberg, E. G., The radium and radon content of Pacific Ocean water, life, and sediments: Am. Jour. Sci. 5th ser., vol. 36, p. 235, 1938. Revelle, R., quoted in Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., op. cit., p. 1034.

Evans, Kip, and Moberg report that kelp and plankton exhibit radium concentrations of about one hundred times that of the water in which they live. Revelle shows a correlation between the radium content of marine sediments and their organic siliceous remains and concludes that dissolved radium is extracted from the water by the diatoms and radiolarians, and is carried to the sea floor in these siliceous remains. It should be noted that the radium in these organisms could not have formed from disintegration of uranium in the plants, and that it must have been taken from the sea as radium, not uranium. Similarly Piggot and Urry (op. cit., p. 83) show that only a small portion of radium in deep sea sediments could have formed from the disintegration of uranium, and that most of the radium must have been removed from the sea as radium and ionium, not uranium. Incidentally, Piggot and Urry (p. 88) think it improbable that organisms "play any major role in producing the high radium concentrations in the surface of the sediments" because "an inspection of the quantitative aspect of their role as carriers of radium to the ocean bottom reveals that they can remove no more than a few percent of the radium from their habitats each year" and in addition "it is known that their remains mostly dissolve before reaching any profound depth."

[38] Newman, W. F., The distribution and excretion of uranium: U. S. Atomic Energy Commission, Absts. of Declassified Documents, vol. 1, no. 3, p. 149, Sept. 1947.

[39] Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., op. cit., pp. 252–263, 916–917, 1942.

Nelson [40] believes that organic precipitation might explain the apparent concentration of uranium in the older, Paleozoic shales, for if the uranium concentration in sea water is a function of the amount brought from the land and the amount taken out by marine organisms, and if no organisms that could selectively remove uranium existed in Precambrian seas, then the uranium concentration in sea water should have been highest in late Precambrian time; large amounts of uranium would have been available in the sea by Cambrian time when organisms developed that could selectively remove it. This apparent age relationship may be disproved on further exploration, of course, and if it does exist it may have other explanations.

Adsorption.—A number of investigations have suggested that uranium may be adsorbed by clay, organic matter, or other finely divided material. As previously mentioned, Beers reports that certain clays can adsorb large quantities of uranium in the process of settling through a solution containing uranium. Beers and Goodman [41] emphasize that all the uraniferous sediments contain some shale, organic matter, or other material which was in a very finely divided state at the time of deposition. They point out that limestone and sandstone are not measurably radioactive unless they contain some material once in a very finely divided form, and conclude that the radioactivity in sedimentary rocks appears to be the result of concentration in a colloid environment.

Hoogteijling and Sizoo [42] tested the radioactivity, potassium, and zircon content of a number of specimens of different clay minerals. In the specimens tested, a small part of the radioactivity was due to potassium, but none of it was due to zircon; they found no relation between the concentration of radioactive substances and the type of clay mineral present, but did find that the radioactivity increased with decrease in grain-size of the clays. They concluded that "during the chemical transformation of the original minerals into the clay minerals the radioactive elements are at least for a part unbound and spread over the whole material by adsorption to the surface of the precipitating particles."

Tolmachev [43] has shown that the UO_2^{++} ion is reversibly adbsorbed by activated carbon, and that shales from Central Asia and the Leningrad region adsorb uranium irreversibly, possibly through some chemical reaction. Because the shales that have the greatest initial uranium content have the greatest adsorptive power, he believes that the shales initially acquired uranium by adsorption. A somewhat similar view is expressed by Fredrickson [44] who thinks it possible that UO_2^{++} ions, after their release on weathering from igneous rocks, are adsorbed by ionic exchange phenomena on layer-lattice minerals such as certain clays, and then (because of an increase in temperature, aging of the material, or the introduction of chemically more active ions into solution) displaced again and put into solution; carbonaceous material in the

[40] Nelson, John M., U. S. Geol. Survey, report in preparation.

[41] Beers, R. F., and Goodman, Clark, op. cit., p. 1251.

[42] Hoogteijling, P. J., and Sizoo, G. J., Radioactivity and mineral composition of soil: Physica, vol. 14, no. 6, pp. 357–366, 1948.

[43] Tolmachev, U. M., Adsorption of uranyl salts by solid adsorbants: Acad. sci. U.S.S.R. Bull. no. 1, pp. 28–34, 1943.

[44] Fredrickson, A. F., op. cit.

path of the displaced ions then might fix the displaced ions by adsorbing them between the graphitic layers of carbonaceous material.

Adsorption (*i.e.*, the attraction of a foreign body to the surface of a given substance) involves a number of different processes, some known under different names to workers in various fields, and before discussing further the adsorption of uranium, it is appropriate to review the various processes known as adsorption.

Two general kinds of adsorption have been recognized:[45] (1) physical or van der Waals adsorption and (2) chemical adsorption. Physical adsorption is characterized by low heats of adsorption and by a loose bonding of the adsorbate to the adsorbent; it is probably of little importance in the concentration of uranium in sediments, both because the amount of uranium adsorbed is apt to be very small, and because it is only loosely held. Chemical adsorption, on the other hand, is characterized by high heats of adsorption and a firm, chemical bonding (*i.e.*, by valence bonds) of the adsorbate. It may involve the bonding of a foreign cation or a foreign anion, or both, to open bonds at the surface of a substance; or it may involve the exchange or substitution of a foreign cation or anion, or both, for a cation or anion at the surface (even an interior one).[46]

The amount of adsorption and the selection of ions adsorbed is governed by a number of rules or laws, some of the most pertinent of which are:[47]

1. "A cation will be adsorbed by a salt of low solubility when it forms with the anion of the adsorbing salt a compound, the solubility of which in the solvent is small;" the amount precipitated increases more or less with decreasing solubility of the compound formed.[48]

2. The adsorption of an ion is favored if the compound formed is isomorphous with the adsorbent[49] and if the ion is similar in size to one of those of the crystal lattice.

[45] Prutton, C. F., and Maron, S. H., Fundamental principles of physical chemistry, p. 232, Macmillan Company, New York, 1944. Mantell, C. L., Adsorption, p. 3, McGraw-Hill, New York, 1945.

[46] Koltoff, I. M., and Sandell, E. B., Textbook of quantitative inorganic analysis, pp. 103–117, Macmillan Company, New York, 1936.

Chemical adsorption includes processes that may also be known as coprecipitation (a general term in analytical chemistry for the contamination of a precipitate by substances that are normally soluble under the conditions of the precipitation); surface adsorption (a general term for the attraction of contaminating ions to the surface of the crystals of a precipitate); occlusion (the process by which foreign ions attracted to the surface of a crystal are included within it as the crystal grows); ion exchange or exchange adsorption (the exchange of an ion on the surface, even an interior one, of a solid for one of the solution, in contrast to the attachment of an ion from a solution to an open bond on the surface); and isomorphic substitution (the substitution or proxying of one ion for another of about the same size). All of these processes do not always involve adsorption; for example, isomorphous substitution of one ion for another is not restricted to the surface, but when such does occur at the surface, it is one kind of chemical adsorption. It should be evident also that these various processes are not necessarily distinct from one another. Depending upon the ions and compounds involved, the replacement of one ion by another might be properly described as both isomorphous substitution and exchange adsorption; and if the exchange took place during crystal growth, the adsorption might be described as occlusion.

[47] See Koltoff and Sandell, op. cit., for a good discussion of some of the other laws not repeated here.

[48] Hevesey, G., and Paneth, F. A., A manual of radioactivity, p. 163, Oxford University Press, London, 1926.

[49] Idem, p. 164.

3. The amount of adsorption increases as the grain size decreases and the surface area (including internal surfaces) increases.

4. The amount of adsorption increases with increasing speed of formation of the precipitate or growth of the crystals, especially when the compound formed with adsorbent is not highly soluble.

The type of adsorption referred to by Tolmachev, Beers, Fredrickson and others is evidently chemical and the adsorbing capacity of clay and especially isomorphous carbon is, as Fredrickson points out, due in part to their extensive internal structure and unsatisfied valencies. As many clays and carbonaceous shales are not appreciably uraniferous, it seems evident that other factors also control the adsorption of uranium. Possibly the most important of these are the local variations (or the factors controlling them) in the solubility of the uranium salts in the sea as well as the solubility of the compounds they form with the adsorbents. Whatever may be the chemical or physical factors that favor the adsorption of uranium, at least one factor—the presence of carbonate—inhibits the precipitation or adsorption of uranium. Piggot and Urry [50] have pointed out that in the laboratory "the precipitation of uranium is inhibited by the presence of the carbonate ion" and that such a relationship exists in nature is shown by the aforementioned negative correlation between uranium and carbonate in both the shales and the phosphates.

Although adsorption has thus far been considered only with respect to the origin of the uranium in the shales, it is possible, if not probable, that uranium may be removed from sea water by adsorption on precipitating phosphate, substituting for calcium (which has an ionic radius nearly identical with that of uranium) in the fluorapatite structure. Such a process might be favored by the strong chemical affinity that exists between uranium and phosphate, shown by the many uranium-phosphate minerals and compounds,[51] as well as the relative insolubility of the compound formed (though the uranium in the western phosphate rock is acid-soluble, it is not leached out in the course of weathering, even where weathering has been so intense that the organic matter, carbonate, vanadium and other minor elements have been removed). Adsorption of uranium by phosphate is probably inhibited by the presence of carbonate ion in the sea water.

Direct inorganic precipitation of phosphate would mean that the sea was saturated with calcium phosphate, however, and this may well have been true. Deitz, Emery, and Shepard [52] believe that the sea water, below a depth of a few hundred meters, is saturated with tricalcium phosphate at the present time. Although the actual phosphate content of the sea varies widely, it appears that the bulk of the phosphate coming to the sea must be precipitated more or less continually though not in equal amounts everywhere. Kaz-

[50] Op. cit., p. 89.

[51] Dement, Jack, and Dake, H. C., Uranium and atomic power, pp. 134–140, Chemical Publishing Co., Inc., Brooklyn, N. Y., 1941.

[52] Deitz, R. S., Emery, K. O., and Shepard, F. P., Phosphorite deposits on the sea floor off southern California: Geol. Soc. America Bull., vol. 53, p. 836, 1942. Also Rubey, W. W., U. S. Geol. Survey, unpublished investigations on the origin of phosphate deposits.

akov [53] and later Rubey [54] have shown that the precipitation of phosphate from the sea water is related primarily to the CO_2 content, pH, temperature, and pressure. The most favorable place for the precipitation of phosphate is on or near the edge of the continental shelves, where the pH of ascending deep, cold waters, rich in phosphate, rises as the temperature increases and the partial pressure of CO_2 decreases. Such precipitation, during times when little else in the way of sediment was deposited, is believed to account for the origin of the phosphate in the Phosphoria formation.

The substitution of uranium for calcium in the phosphate mineral might take place at any time after the precipitation of the phosphate. This may explain the lack of a constant uranium-phosphate ratio; the lack of a concentration of uranium in the nonmarine residual phosphate deposits; and the relative concentration of uranium in the phosphate of the Bone Valley formation as compared to that in the phosphate of the Hawthorn formation from which the Bone Valley was derived, at least in part. The amount of uranium in the phosphate mineral may be a function of the concentration of uranium in the sea at the time of deposition of the phosphate, as well as of the length of time a phosphate mineral particle is exposed to the uranium-bearing solution. Phosphate precipitated in the sea at times or places where the sea contained subnormal amounts of uranium would contain less uranium than it could if the sea were more uraniferous. Similarly, precipitated phosphates exposed to the sea water only a short time, either because they were quickly deposited or buried after precipitation, would contain less uranium than those mineral particles that were exposed to the sea for a long period, either because they remained in suspension for a long time after their precipitation or because they were exposed to sea water for long periods after their deposition.

The difference between the less uraniferous phosphate of the Hawthorn formation and the more uraniferous phosphate of the Bone Valley formation may have its explanation in the fact that the phosphate of the Hawthorn was deposited as a relatively minor constituent of the formation and was buried by other materials before it was exposed to the sea long enough to take up much uranium. In the transgression of the sea over the buried Hawthorn formation, the Hawthorn was exhumed gradually and its sediments reworked by the sea during Bone Valley time; most of the non-phosphatic material was removed but some of that remaining (such as some carbonate fragments) was more or less phosphatized, and all the phosphatic material had opportunity to acquire more uranium through renewed exposure to the sea water.

The residual hard-rock phosphate of Florida, which was concentrated by weathering of a phosphatic limestone, may be less uraniferous than the bedded phosphorites merely because the phosphate was not concentrated in the presence of uraniferous solutions, such as the sea water. Though the parent phosphatic formation (the Ocala limestone) was of marine deposition, its phosphate, like that of the Hawthorn formation, was deposited and buried be-

[53] Kazakov, A. V., The phosphorite facies and the genesis of phosphorites, *in* Geological Investigations of Agricultural Ores: Scientific Inst. Fertilizers and Insecto-Fungicides Trans. no. 142 (published for the 17th session of the International Geological Congress), Leningrad, pp. 8–21, 1937.

[54] Rubey, W. W., U. S. Geological Survey, unpublished investigations.

fore it was allowed to acquire much uranium. Had it been concentrated by reworking in a marine environment, as was the Bone Valley, instead of by weathering at the surface of the land, it might be as uraniferous as the phosphate of the Bone Valley formation.

The theory that uranium was removed from the sea by its substitution for calcium in the phosphate mineral or its chemical adsorption by organic matter or clay seems in harmony with the facts available to us and partly explains some of the variations in the uranium content of the phosphorites and black shales. Although the presence of carbonate ion seems to inhibit the adsorption of uranium, the physico-chemical conditions that favor its adsorption are unknown.

Concentration of Uranium in the Sediments.

On the supposition that uranium can be precipitated and fixed in the sediments in one or more of the ways just described, its concentration will result, of course, from conditions that lead to the concentration of phosphate, organic matter, clay, or other substances, which may have taken the uranium out of solution. Such circumstances may be varied, but one basic set of conditions is of paramount importance—deposition in a marine basin in which the environment does not favor influx of large amounts of clastics or precipitation of large amounts of carbonate, either of which would tend to dilute and quickly bury the uranium-bearing sediments. The development of such an environment is the result of the interplay of many factors, such as those controlling the height of the adjacent lands; the size, depth, and configuration of the basin of deposition; and the climate, both as it affects the vegetative cover on the land and controls the rate of erosion, and as it affects photosynthesis and temperature in the sea.

Guides to the Search for Uranium in Marine Sedimentary Rocks.

We know of no better way of expressing our evaluation of the data available on the occurrence and origin of uranium in sediments than by saying that the U. S. Geological Survey will continue to measure the radioactivity of rocks of every type; we hope others will do likewise. But circumstances, among which is the life span of man, require every prospector to restrict his efforts to the areas or rocks that appear most promising, and the following recapitulation of observed and interpreted facts may serve temporarily as a guide as to which sedimentary rocks and areas are most likely to contain uranium.

Marine black shale and marine phosphorite, especially in relatively thin formations believed to be the depositional product of long periods of geologic time, are likely to contain significant concentrations of uranium. Worthy of examination, too, are marine rocks likely to have been deposited in a colloidal, or finely divided state, and to have accumulated slowly, such as iron,[55] man-

[55] Iron hydroxide is utilized as a coprecipitator of uranium and some other radioactive elements in some of the laboratory analytical methods (Urry, W. D., The radioactive determination of small amounts of uranium: Am. Jour. Sci., vol. 239, p. 193, 1941) and Pettersson (op. cit.) has suggested that thorium and ionium are removed from sea water by coprecipitation with iron hydroxide.

ganese, and glauconite deposits in particular, and clay and shale deposits in general.

In this country, rocks of the above types are found in some formations of Paleozoic and early Mesozoic age in the Rocky Mountain region of the Western States; and some of pre-Mississippian age in the Appalachians and in the Central States. Excluded from this concept of concentration of uranium are rocks deposited during and for sometime following major orogenies or periods of mountain building in the areas adjacent to those uplifts. Such disturbances are the Acadian disturbance in late Devonian and earliest Mississippian time and the Appalachian revolution in Permian time in the Eastern States; the Nevadian and Laramide revolutions in the Mesozoic in the Rocky Mountain region; and the Cascadian revolution of the Pacific coast. Marine rocks, especially black shales and phosphorites or other rocks of slow deposition, deposited in those regions prior to the inception of the periods of important mountain building, are most likely to contain significant concentrations of uranium, and those deposited after these periods are least likely to contain such concentrations. It should be emphasized, however, that the theories of origin presented would permit, albeit under special circumstances, uranium to be concentrated in the rocks and areas here considered less promising; we hope they will be tested in spite of our negative recommendations.

Many of the formations that have the characteristics of uraniferous sedimentary rocks have been tested at one or two localities and found not to contain much uranium; others have not been tested at all. Examples of those which appear most deserving of further exploration are: the Ordovician Normanskill and Deepkill shales in New York State and New England, and the phosphatic portion of the Swan Peak quartzite in Utah and Idaho; the Silurian Clinton formation in the Appalachians; the Devonian Percha shale in New Mexico, the Antrim shale in Michigan, the Mountain Glen shale in Illinois, the Huron shale in Ohio, the Oriskany formation (phosphatic and manganiferous part) in Virginia, and the basal phosphatic part of Chadwick's Bishop Brook limestone in New York; the Devonian and Mississippian Ohio shale in Ohio; the Devonian or Mississippian Grassy Creek shale in Missouri and Cleveland shale in Ohio; the Mississippian Brazer limestone (phosphatic portion) in Utah, Wyoming, and Idaho, the Deseret limestone (black shale and phosphatic zone at the base) in Utah, the Caney shale in Oklahoma, the Helms formation in western Texas, and the Sunbury shale in Ohio; and the Pennsylvanian Cherokee shale in Kansas and Missouri and the Bandera shale of Kansas and Oklahoma.

Methods of Prospecting.

Methods of prospecting, including a full explanation of the use of the Geiger counter, have been described in a prospectors manual.[56] A few suggestions, however, may be appropriate.

[56] Prospecting for uranium: U. S. Atomic Energy Commission and the U. S. Geological Survey, 123 pp., 1949. See also Faul, Henry, Radioactivity exploration with Geiger counters: Am. Inst. Min. Eng. Tech. Pub. no. 2460, pp. 1–18, 1948.

In the uranium occurrences described, no uranium-bearing mineral has ever been recognized visually. The mere fact that a rock does not contain lustrous minerals is no indication that it does not contain uranium. Carbonaceous matter generally can be seen by inspection, and certain types of organic matter can be identified by simple tests described by Russell.[57] High concentrations of phosphate can be identified by a simple method devised by Rubey.[58] Radioactivity can be measured by a Geiger counter, but uranium in trace amounts cannot be distinguished from other radioactive substances or determined accurately except by very exacting and newly devised chemical methods.

Prospecting for uranium and thorium with a portable Geiger counter is basically simple. The counter's response to radiations from radioactive materials and cosmic rays is in the form of pulses or clicks; the rate at which these pulses are received is a function of radioactivity. If the response is greater at one spot than another, the radioactivity of the source material can be localized by repeated traverses across the rock or soil. If the response of source material is four or more times normal "background," the rock should be sampled and sent to a laboratory for quantitative analysis.

Another important point to remember in prospecting for uranium is that a given formation cannot be considered non-uraniferous until every bed has been exposed and tested. It is not enough merely to test one or two layers and to take them as representative of the whole. For example, scores of beds in the Phosphoria formation look alike and might appear to have the same composition; yet analyses of individual layers show that nearly every bed has a different composition as regards its minor-element content, and unpredictably so.

Similarly, a given formation cannot be considered non-uraniferous everywhere merely because it is so at one locality. The marine black shale and phosphorite deposits are noted for the great lateral continuity of their layers, but the minor-element content is known to vary considerably over short distances in certain areas. In the exploration of the Phosphoria formation we are trying to channel-sample every bed in the phosphatic shale member at intervals of 3 to 6 miles, yet we have had to recognize the fact that any individual sample may not fairly represent the content of any given element, even the major ones, in that area. We find it worthwhile to remind ourselves frequently that our knowledge of the distribution of uranium is by no means a substitute for sampling.

ACKNOWLEDGMENTS.

So many people and organizations have taken part in the studies on which this paper is based that it is difficult to know where to begin in acknowledging their contributions. The Geological Survey's Trace Elements investigations were begun in 1943 at the request of the Manhattan District Corps of Engi-

[57] Russell, W. L., Some characteristics of organic content of rocks: Am. Assoc. Petroleum Geologists Bull., vol. 18, pp. 1102–1125, 1934.

[58] Published in Gardner, L. S., Phosphate deposits of the Teton Basin area, Idaho and Wyoming: U. S. Geol. Survey Bull. 944a, p. 16, 1944.

neers; its successor, the Atomic Energy Commission, has continued to defray the major part of the cost of the investigations. We are indebted to them, not only for financial support, but for permitting us latitude, in as much measure as their own charter and circumstances allow, to investigate some of the scientific as well as the economic aspects of the occurrence of uranium. We are especially indebted to Lt. Col. Paul L. Gaurin, Col. A. W. Oberbeck, Lt. Col. Gordon Page, P. L. Merritt, H. D. Keiser, John K. Gustafson, and C. K. Leith (an advisor to the Commission) who have personified this Commission policy.

The Survey's investigations were begun under the inspirational and imaginative leadership of W. W. Rubey; the fact that most of the important deposits discovered by the Geological Survey were found by parties under his direction within a few months after the initiation of the study is a tribute to his penetrating analysis of data then available on the occurrence of uranium. T. B. Nolan, Assistant Director, likewise has made an important contribution through his continued interest and support.

The results of most of the Survey's field studies are of course not reported here, but have been drawn on for the principles they help prove or indicate. These investigations were conducted by a number of other Survey geologists as well as ourselves, principally F. C. Armstrong, K. G. Brill, A. P. Butler, C. W. Chesterman, S. E. Clabaugh, J. O. Harder, W. H. Haas, F. Stearns MacNeil, C. E. Prouty, J. C. Rabbitt, A. L. Slaughter, L. E. Smith, F. W. Stead, Helmuth Wedow, and D. G. Wyant.

F. W. Stead designed and constructed many of the Geiger counters used in the field work, and was in large part responsible for perfecting methods for their use and interpretation.

Geological Survey chemists have likewise made essential contributions to the investigations, not only in analyzing samples, but in developing reliable analytical methods. Deserving of special mention are Michael Fleischer, F. S. Grimaldi, W. G. Schlecht, M. D. Foster, W. T. Schaller, R. E. Stevens, and K. J. Murata.

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UNIFORMITARIANISM AND THE IDEAL VEIN.[1]

HARRISON SCHMITT.

ABSTRACT.

Construction of the ideal vein with the assumption that the theory of uniformitarianism applies throughout Earth history is questioned. Certain data suggest that some types of mineral deposition may be unique with time. Data given by Jeffreys and Daly strongly indicate that the Earth and particularly the Earth's crust has changed fundamentally with time. Present day theory implies that vertical zoning of genetic types should be common; actually it is rare. This suggests the need for competing hypotheses of "mineralization" genesis. The depth classification of mineral deposits by metal content is unsatisfactory. For example, Tertiary deposits of epithermal character contain commercial deposits of metals which would normally be said to be characteristic of the "deep zone." Although the majority of elements seem to persist in the various ore mineralizations throughout Earth history certain ones may be quantitatively unique with time. Mercury, selenium and tellurium seem characteristic of late time. Sulphur chemically related to the last two elements seems to have been unevenly distributed in early time. Another chemical group, bismuth, arsenic and antimony may be characteristic of late time.

THE organization of this paper began soon after reading Jeffreys and Daly (9, Chaps. II and III)[2] on the origin of the Earth. These authors advance convincing arguments for marked changes in the Earth from its birth to the present time. This suggested not only that the fairly widely approved hypothesis of the ideal vein and the superposition of depth and temperature types of ore deposits might be vulnerable to attack on the score of uniformitarianism, but as the study progressed the writer began to wonder how the hypothesis could have grown to its present standing, extension and complication without having encountered more written scepticism than it has. Emmons (5) and Graton (7, 8) seem to be the chief proponents of the "theory." Buddington (2), Butler (3) and Dougherty (4) suggest modifications and/or objections.

The original basis for the "theory" seems to have been the fact that the higher the temperature of origin of a deposit the usually greater determined depth of origin. There is common horizontal zoning of metals, if not of genetic types of deposits, and some rare vertical metal zoning. Close metal zoning is observed in carbonate rocks and in non-carbonate rock epithermal vein environments. The natural inference is that since hypogene mineralization often is seen to extend down the higher temperature types should appear in depth. Furthermore, the "theory" fits well into the most widely held eclectic theory of the relationship of igneous rocks and ores.

[1] Presented to the Society of Economic Geologists, San Francisco meeting, February 15, 1949.

[2] Numbers in parentheses refer to Bibliography at end of paper.

Objections to the ideal vein and related depth-temperature zone "theory" are composed of fact and inference. They are first summarized as follows: (1) No ideal vein or full sequence of depth-temperature zones seems to have been described. (2) In non-carbonate rocks observed transitions of one type of depth-temperature zone to another are rare if they exist. (3) Many important veins explored for thousands of feet in depth show little change in character of mineralogy. (4) The factors of depth and temperature are not linked in simple direct proportion. (5) A depth theory based on metals alone encounters contradictions as early sensed by Graton. (6) Zones, usually of metals not of genetic types, in carbonate rock and epithermal environments may not be examples of type zoning on reduced scale. (7) As paragenetic studies are advanced we sense an impasse in temperature typing of many deposits. This makes it possible to fit uncertain types into almost any one's scheme of zoning. (8) As the history of the Earth is now viewed, compilation of an ideal vein on the basis of the theory of uniformitarianism, that is, compilation by means of veins and other types of deposits of *widely differing ages* may be untenable.

(1) So far as this writer knows no complete ideal vein has been described. It may not be fair to expect that one exists though it would seem that somewhere a compression of isotherms should have given rise to an exposed full sequence particularly near intrusives.

(2) The general lack of transition of the epithermal to the mesothermal mineralization is well known. Loughlin and Behre say (13, p. 32):

> Most of the epithermal deposits, those formed at relatively low temperature and for the most part shallow depths, are not traceable into deposits typical of those formed at greater depth, and some at least of the most productive epithermal deposits in the western United States were formed at a *distinctly later age* (ital. HS) than the mesothermal and hypothermal deposits of the same region.

The barren zone postulated to separate the epithermal from the mesothermal seems doubtfully to ever give way to mesothermal in depth, this despite presumably wholly adequate post-ore erosion in many areas of epithermal veins. Graton, however, (8, pp. 543–4) argues that the so-called barren zone is merely the expression of the loss of the precious metals and that the base metals continue down. The difficulty is, in this writer's experience, at least, in the Southwest and northern Mexico, that the epithermal vein ore shoots usually bottom in barren quartz, mineralized breccia or if in sulphides these soon pinch out. This writer suggests that the case of Casapalca, Peru (14) is possibly not ready for final conclusions as to what the higher copper content means in depth. At Goldfield, Nevada, the main ore shoot bottomed in copper ore, but this soon pinched out. Ore shoots of the Veta Colorado at Parral, Chihuahua, first bottom in massive sulphides, then, a few hundred feet deeper, in barren breccia. Is not this occasional zoning to mesothermal aspect in depth merely the often described "telescoping" of epithermal veins? Broderick (1a) thinks the Michigan copper lodes are epithermal grading to mesothermal in depth. The mesothermal ores in noncarbonate rocks, so far as this writer knows, do not progress to hypothermal in depth.

Many hypothermal deposits grade into pyrometasomatic upon change to a carbonate wall, but as Graton (8, p. 531) and Loughlin and Behre (13, pp. 48–49) indicate we should not place these two types in separate classes on the basis of temperature and pressure. The latter authors also say (13, p. 50):

> The transition from pegmatites into massive quartz veins . . . has led some to maintain that there is a continuous transition through these veins into metalliferous veins, but, if any such transitions have been proved, they are extremely rare.

In carbonate rocks transitions from, by definition, mesothermal replacements, mantos and bedded deposits to pyrometasomatic replacements, *i.e.*, hypothermal, are not uncommon. Examples that come to mind are found at Santa Eulalia, Chihuahua, Leadville, Colorado and Hanover, New Mexico. It seems uncertain if this zoning, which is often horizontal only, has meaning in terms of the ideal vein or depth zones. It may not indicate differences in temperature of origin of the sulphides for those which cut and replace the pyrometasomatic silicates may have done so at a temperature no higher than was the case in the mesothermal environment.

(3) A number of important mineral deposits persist thousands of feet in depth with nearly imperceptible changes in mineralogy and tenor. The fact that these deposits vary from Precambrian to Tertiary in age might argue that changes in the Earth and its crust have not affected ore deposition conditions. Graton (7, 8) suggests that the "depth zones" are so high that we are not likely to see transitions. He goes on to say (7, p. 193):

> There seems every reason to suppose that the leptothermal, mesothermal and hypothermal zones underlie the epithermal just as these zones successively underlie one another.

The use of a dozen or so unusual mines however, as a basis for generalizations may be questioned. Probably more than 99 percent of all mines have proved to be small and to have little persistence in any direction.

(4) The terms hypothermal, mesothermal and epithermal seem originally used by Lindgren to imply proportional depth and temperature. It seems clear now, however, that deposits formed at shallow depths can originate at high temperatures (2, 3, 4) and perhaps some deeply formed deposits may form at abnormally low temperatures. The depression of isotherms in geosynclines or depressed fault blocks may be pertinent here. Lindgren's terms perhaps should be restricted to depth implication only and modified somehow. Perhaps to designate temperature, compound terms should be used or even added phrases. Epithermal-hot (xenothermal) or hypothermal-cold would, however, certainly be upsetting. Most of us resist the introduction of new terms, but the conventional structure is getting unwieldy. The problem is further complicated by the fact that paragenesis reveals widely variable temperatures of deposition in many deposits.

(5) An ideal vein hypothesis based on a depth zoning of metals as suggested by Emmons (5) runs into many contradictions as was early sensed by Graton (8, p. 549). Tellurium is found in veins of deep origin in Canada.

Tin, tungsten, platinum and copper are found in shallow deposits particularly in the Pacific region.

(6) The zoning of types found in carbonate rocks near intrusions and in epithermal deposits may not be small scale patterns of the juxtaposition of types demanded by the zonal theory. The vertical metal zoning in the epithermal deposits is not consistent. In areas of limestones and pre-ore stocks lead, zinc and copper are commonly horizontally zoned on a metal pattern but in depth do not usually repeat this pattern. Much metal zoning is dependent on wall rock changes rather than temperature.

(7) As paragenetic studies are advanced there is sensed greater uncertainty in classifying many deposits as to temperature. When the range of temperatures of origin of most minerals can be determined this uncertainty may be found to be still greater. What should one do with predominantly leady ore replacing garnet or telluride veins cutting "high temperature" silicates? B. S. Butler suggested to the writer that late sulphides replacing garnet may be deposited in about the same temperature range as in deposits without silicates. What mineral or minerals or what criterion is to determine the temperature class? Obviously there is a good deal of room for personal preference in typing on the basis of temperature of origin.

(8) The theory of uniformitarianism was tacitly assumed to apply when the hypothesis of the ideal vein was developed. That essentially uniform conditions guided *surface* geological processes for most of the history of the Earth has been justly questioned only perhaps for Precambrian as against later time. Bastin (1, p. 302) has summarized Gibb and others as follows:

> The presence of such thick and extensive deposits of iron oxides associated with cherty silica in Precambrian rocks in so many parts of the world, and their rarity in younger rocks, points clearly to conditions fundamentally different from those in post-Cambrian times, and indicates that uniformitarianism as a working principle for the geologist cannot be pushed indefinitely into the past.

Discounting the effect of erosion which has removed much of the ground and therefore much of the evidence that existed above old deep-seated ore deposits, and has failed to expose much deep-seated ground below young deposits, some old deposits appear to have unique characteristics as compared with young deposits of the same general class.

Recent authoritative data and conclusions on the origin of the Earth (Jeffreys 9, pp. 11–40) suggest that the Earth, solar system, and possibly the known universe are approximately of the same age, that is, two to three billion years. After a catastrophic stellar origin the Earth rapidly condensed from the gaseous state to a density-layered molten mass which soon crusted over. The time before late Archean (Daly 9, pp. 55–56) as revealed by features of the basement complex was marked by a higher vertical temperature gradient, thinner crust, more abundant near surface magmas and consequently more widespread heat metamorphism than was characteristic later. In other words, the evidence marshalled by Jeffreys and Daly strongly suggest that the basic character of the Earth has undergone a marked change with age. This may have had a critical bearing on the origin of the ore deposits of the

different epochs, that is, ore deposits of different ages are likely to have been influenced by conditions fundamental to the Earth unique with time as well as by the more commonly considered influences of temperature, depth, wall rock, structure, etc.

Precambrian deposits such as the enigmatic oxides at Franklin Furnace, New Jersey [3] and Långban, Sweden, the nickel-cobalt-silver-copper deposits with native metals, certain pyritic deposits of Norway which many are willing to accept as injected in origin, are in contrast to younger deposits with their large proportion of the mesothermal and particularly of the characteristic epithermal deposits. No examples of this latter type,[4] so far as this writer is aware, have been described of Precambrian age in Precambrian terrain which, however, includes volcanic and sedimentary rocks of shallow origin.[5] In other words, most of the epithermal and particularly the "bonanza" silver-gold and the cinnabar deposits may well be characteristic of the later stages of the Earth's history; most of the "injected" sulphide deposits—if their favored theory of origin can stand up under further scrutiny—may be characteristic of the early epochs only when abundant, large, shallow magmas may have promoted the injections of sulphide "matte" near the surface.

Most of the elements seem to have been freely deposited at all times in the crust in the various types of ground conditions and structural forms available to them. In the past several decades numerous data have been published indicating that large commercial deposits of tin, tungsten, copper, and even platinum, metals usually considered as most commonly deposited in deep environments occur in definitely shallow though hot environments mostly Tertiary in age. One may note such outstanding examples of non-conformity as the epithermal tin and tungsten and the "shallow" Teniente copper deposits (12) in the South American Cordillera, the "shallow" platinum deposits in the important Waterberg district of South Africa (16) and the "shallow" high temperature Ashio copper mine of Japan (10).

On the other hand, in early time sulphur may have been unevenly distributed and less abundant in ore depositing fluids. We have noted the sulphur-deficient Franklin and Långban deposits. Hypogene native metals particularly gold and silver seem to have been more prominent. In late time

[3] The writer visited Franklin Furnace in 1946. He was guided through the mine by Allen Pinger. Probably like others he was struck by the close general resemblance to the characteristic contact pyrometasomatic deposits in limestone in the Western Cordilleras except that sulphur is largely absent. The paragenesis outlined by Pinger is: Pegmatite is replaced by andradite garnet which is replaced by willemite. Except that the zinc is not tied up as a sulphide, this mineralogy and paragenesis is broadly similar to many contact pyrometasomatic deposits in the West. There are minor late sulphides, which, however, may be post-Cambrian.

[4] The Lake Superior copper deposits may be an exception for they resemble the epithermal type. Emmons (6, pp. 68, 310–315) Lindgren (11, pp. 514, 517–526) and Broderick (1a) consider them to be epithermal and Broderick thinks they grade to mesothermal in depth. Their Precambrian age has been established. The zoning in depth may represent telescoping. At first consideration they seem to differ greatly from the normal epithermal type. Their unique character in a large part, however, seems to have been conditioned by the high ferric iron content of the walls. It should be noted that their age is Keweenawan which is moderately late in the age of the Earth.

[5] Vulcanism and epithermal mineralization should favor uplifts which should be areas of first and rapid erosion, so the evidence may have been largely destroyed as is argued by opponents of the writer's general theme.

tellurium and selenium, chemically related to sulphur, may have been more abundant in ore deposition (6, p. 468). This is perhaps true also of mercury and of the chemically related group of bismuth, arsenic and antimony (6, p. 456).[6]

The fundamental contrast in conditions of deposition where the walls are carbonate rock or non-carbonate rock, or where the deposition is under conditions which form epithermal deposits as against those which form non-epithermal, should be considered when compiling an ideal vein. This in addition to the need for keeping separated deposits of widely differing ages. As noted, zoning is often developed horizontally in carbonate walls, but vaguely if at all vertically.

It might be of interest to know what proportion of mineral deposits are found in carbonate as against non-carbonate walls. Since carbonate rock is one of the most resistant to erosion there should be an increasing accumulation of it with time in the Earth's crust. With time also, there may have been a decreasing amount of non-carbonate Precambrian basement rock available at shallow depths. This suggests that an attempt should be made to determine if the older deposits are or are not in general more persistent in depth. A deposit in carbonate walls seldom if ever persists into a non-carbonate basement.

There is increasing evidence favoring the belief that the epithermal deposits, possibly including the Mississippi valley variety in carbonate walls, are formed in the shell of meteoric water through the agency of "volcanic" emanations with magmatic water subordinate in quantity. This problem is being reviewed by the writer in a paper to be submitted soon.[7] As others have noted the so-called "telescoping" and "dumping" characteristic of these deposits may well be due to the effect of cold meteoric water as well as to the more open ground conditions near the surface. Thus, there may be a more fundamental genetic contrast than perhaps has been emphasized between the epithermal deposits and the non-epithermal deposits. As suggested earlier, the factor of time may also have increased this difference. The writer (15) uses this contrast as well as that caused by carbonate and non-carbonate walls as a basis for a proposed field classification of mineral deposits which emphasizes the factor of lateral and depth persistence.

This paper is a "trial balloon." The writer hopes that it will stimulate the observation and accumulation of data pertinent to the subject discussed.

SUMMARY OF CONCLUSIONS.

(1) The ideal vein theory implies that transitions from one temperature-depth class of mineralization to another should be common. On the contrary

[6] Graton in 1933 (8, p. 552) made this apparently contradictory statement: "No provision seems necessary for any genetic differentiation on the basis of age, which has so long been emphasized by the German school. Possibly the deep-lying sources are *with the passage of time* (ital. HS) being gradually exhausted of their volatiles and their metals, and thus there may exist a progressive change in quantity and character of ores from early to late geologic time. But we are as yet unprepared with specific data whereby to check this idea."

[7] The fumarolic-hot spring and epithermal mineral deposit environment, prepared for presentation at the Seventy-fifth Anniversary of the Colorado School of Mines, Golden, Colorado, September 30, 1949.

they are rare, particularly if the hypothermal and pyrometasomatic classes are grouped together. Many of the great and deep mineralizations ranging from hypothermal to epithermal show minor if any vertical zoning. They range from Precambrian to Tertiary in age. The metal zoning encountered in carbonate rocks, generally horizontal, and in epithermal veins should not be used to support the ideal vein theory.

(2) Recent data on the origin of the Earth indicate marked changes in the condition of the crust with time. The early crust seems to have been characterized by a high temperature gradient, numerous shallow magmas, much heat metamorphism and perhaps by a minimum of carbonate rock terrain. The epithermal mineralization seems to have been developed weakly if at all for much Precambrian terrain of rocks of shallow origin remains and could have preserved them. This type was strongly developed, however, in the late history of the Earth.

(3) Most of the *elements* seem to have been freely deposited at all times in the crust in the various types of ground conditions and structural forms available to them. One notes that many of the so-called "deep zone" metals; tungsten, tin, platinum and "moderate depth" metals such as copper are fairly common in shallow epithermal deposits of Tertiary age. Exceptions may include mercury, tellurium, selenium, and sulphur which is chemically related to tellurium and selenium. Tellurium and selenium are common in young deposits but uncommon in old deposits.[8] Sulphur appears unevenly distributed in old deposits. Bismuth, antimony and arsenic, another chemically related group, may be more characteristic of late time than early because they are most prominent in mesothermal and epithermal veins.

The above data suggest the following inferences:

(a) Should ideal veins be constructed the data used should be limited: (1) in time, (2) as to carbonate or non-carbonate host, (3) as to epithermal and non-epithermal environment.

(b) One should sharpen one's attention to unique differences in deposits of different ages.

(c) In the epithermal veins it may generally be futile to expect contemporaneous ore deposits below the so-called barren zone.

(d) In deposits other than epithermal however, in non-carbonate walls, it may be that one should have more faith in extension in depth. The exploration of ore deposits in the western Cordillera may have given undue prominence to the characteristics of deposits in limestone and to epithermal deposits. Both show close metal zoning and non-persistence in depth.

The writer is greatly indebted to Drs. T. M. Broderick, B. S. Butler and Augustus Locke and to W. H. Callahan for their interest in, and criticism of, this paper.

SILVER CITY, N. M.,
Sept. 6, 1949.

[8] Most of the tellurium and much of the selenium supply of North America came from Precambrian copper of Manitoba, Quebec, and Ontario. EDITOR.

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A METHOD FOR DETERMINING THE DIRECTION OF FLOW OF HYDROTHERMAL SOLUTIONS.

F. GORDON SMITH.

ABSTRACT.

A method for determining the direction of flow of hydrothermal solutions, using the measured temperature of filling of liquid inclusions in vein minerals, is outlined. The application of the method to the low temperature ore of the McIntyre and Lamaque mines shows that the solutions moved upward in the inclined ore zones under a driving pressure gradient of 400 atmospheres per mile. Relative flow velocities can also be measured in any one vein.

INTRODUCTION.

It is sometimes desirable, both for scientific and practical purposes, to know the direction of flow of hydrothermal solutions which were responsible for the deposition of economic mineral deposits. Methods employing differential etching, and deposition on vuggy crystals, are not entirely unambiguous, and at the present time there appears to be no method in general use. The following method, based on the relative density of liquid inclusions, gives positive results.

If one were able to measure the pressure of the hydrothermal solution during the deposition of any one mineral in various places in a vein system, it would be possible to determine the direction of flow, since the flow must be perpendicular to the iso-baric planes and in the direction of falling pressure. Liquid inclusions in hydrothermal minerals record the density of the solution during deposition, and it is possible to measure the degree of filling of inclusions with considerable accuracy. The density or degree of filling of inclusion is a function of two variables—temperature and pressure, so that in order to determine the pressure, the temperature must be known.

As a first approximation, one can assume that the temperature change during the deposition of any one mineral was of small order and linear over small distances. Consequently, non-linear changes in the density can be ascribed to non-linear changes in the pressure. A more exact method is to determine the temperature gradient by using a geological thermometer which is not pressure-sensitive, such as the thermo-electric potential of pyrite (Smith).[1] Using the latter method, the density change due to the temperature change alone can be calculated, and the calculated pressure gradient necessary in order to keep the density constant if the pressure were constant can be added to the measured pressure gradient which was determined by assuming the temperature was constant.

[1] Smith, F. G., The pyrite geo-thermometer: Econ. Geol., vol. 42, pp. 515–523, 1947.

The decrepitation method of measuring the degree of filling of liquid inclusions in hydrothermal minerals (Scott,[2] Peach[3]) is much more convenient than the heating stage optical method (Ingerson[4]). The former method has been in use for over a year in this laboratory and has been found to be a rapid and accurate method.

It is possible to test the general method of determining the pressure of deposition by measuring the density of liquid inclusions in an ubiquitous mineral such as quartz in a deep mine. The pyrite in the McIntyre Mine at Schumacher, Ontario, has been tested over a vertical range of 1.2 miles (Smith[5]). The same specimens of ore were available for the test of the density gradient. It had been found in the previous study of this ore that there were two periods of mineralization, the first at a temperature of about 510° C and at a pressure equivalent to about 6 miles of rock load, and the second at a temperature of about 150° C and at a very much lower pressure. Since the decrepitation method is more accurate in the low temperature range, the low temperature stage of mineralization was the one selected for the test of the pressure gradient. It had also been found that quartz gives somewhat more consistent decrepitation results than other vein minerals, so that quartz in the veins was the mineral chosen for the series of decrepitation tests.

It had been determined previously that the low temperature decrepitation of quartz from the McIntyre Mine represents secondary inclusions (in quartz crystallized at a high temperature) trapped during the low temperature stage. However, for the purpose of this investigation, it does not matter whether the inclusions are primary or secondary.

DECREPITATION OF QUARTZ.

Quartz from various levels in the McIntyre mine was crushed and sieved to $-20+200$ mesh. Where carbonate minerals were seen to be present the crushed material was washed in concentrated hydrochloric acid and thoroughly dried. A series of test runs before and after acid treatment showed that minor amounts of carbonate and pyrite did not alter the shape of the decrepitation curve in the low range (*i.e.* under 200° C), so that most of the specimens were not cleaned after crushing.

The decrepitation runs were made using the apparatus described by Peach[3] except that the glass tube holding the powder in the furnace was replaced by a stainless steel vessel designed to allow a more uniform heating of the powder and a larger fraction of the powder to contribute to the recorded decrepitation. The optimum amount of powder in the steel heating vessel was found to be 3 to 10 grams, depending upon the number of inclusions per grain.

[2] Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: Econ. Geol., vol. 43, pp. 637–654, 1948.

[3] Peach, P. A., A decrepitation geothermometer: Am. Mineralogist, vol. 34, pp. 413–421, 1949.

[4] Ingerson, E., Liquid inclusions in geologic thermometry: Am. Mineralogist, vol. 32, pp. 375–388, 1947.

[5] Smith, F. G., The ore deposition temperature and pressure at the McIntyre Mine, Ontario: Econ. Geol., vol. 43, pp. 627–636, 1948.

The heating rate was approximately 12° C per minute. The recorder chart rate was 0.5 inches per minute.

The optimum setting of the counting and integrating circuit was found to vary considerably with the size and abundance of inclusions in the quartz, but most of the runs were carried out with a counting rate of either 1 or 10 pops per second for full scale deflection of the recorder.

The beginning of the low temperature decrepitation of the quartz was found to be quite sharp and reproducible. Every specimen tested showed the low temperature decrepitation, but the number of the high density inclusions was found to vary considerably. In most cases two or three runs were made before the optimum setting of the instrument was obtained. It was found that, when a number of runs were made in succession, two determinations, including preliminary decrepitation runs, grinding, and sieving, could be made per hour by one person.

TABLE 1

DECREPITATION TEMPERATURE OF QUARTZ IN THE MCINTYRE MINE

Serial No.	Depth in feet	Vein No.	Decrepitation temperature
251	248	1	172° C
202	726	3	164° C
203	852	2	136° C
221	923	1	126° C
99	1822	7	137° C
119	2033	7	116° C
375	2511	2	115° C
434	2823	2	145° C
447	3356	5	86° C
196	3556	1	100° C
89	3578	1	126° C
486	3771	2	96° C
483	3772	1	108° C
461	4949	1	75° C
504	5272	1	73° C
513	5273	1	87° C
282	6425	12	92° C

The interpretation of decrepitation curves (so-called decrepigraphs) has been discussed by Scott [5] and Peach.[3] At the present time in this laboratory, the interpretation of the curves is carried out in a standard manner which has not yet been described, and which is subject to change as we gain experience in this new technique. The present method is illustrated in Figure 1. Since the same method of interpretation was used throughout this series of tests, and since all of the decrepitation points are at similar temperatures, it was felt that, even though the interpretation method may be quantitatively in error, the decrepitation points are relatively correct. An empirical correction of approximately − 20° C must be applied to all of the quartz decrepitation temperatures before using them to calculate the pressure during deposition. This is based on data given by Scott [5] and Peach.[3]

The data of decrepitation temperatures, sample numbers, vein numbers, and depths from the surface are given in Table 1. The decrepitation tem-

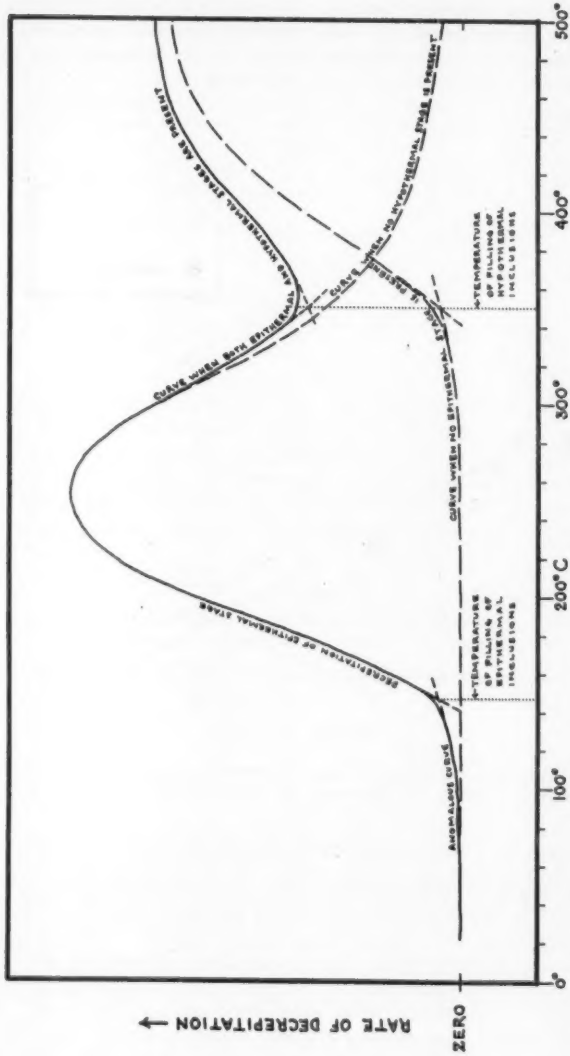

FIG. 1. Average decrepitation curves of quartz from gold mines in Ontario and Quebec, illustrating the current method of determining the temperature of filling of liquid inclusions from the inflections of the decrepitation curves.

peratures are shown in Figure 2 plotted against the depth below the surface. It will be seen that although there is a considerable scatter of the results, there is a well defined trend. It was concluded that with increasing depth in the mine the decrepitation temperature of quartz decreases at a rate of approximately 70° C per mile (43° C per kilometer).

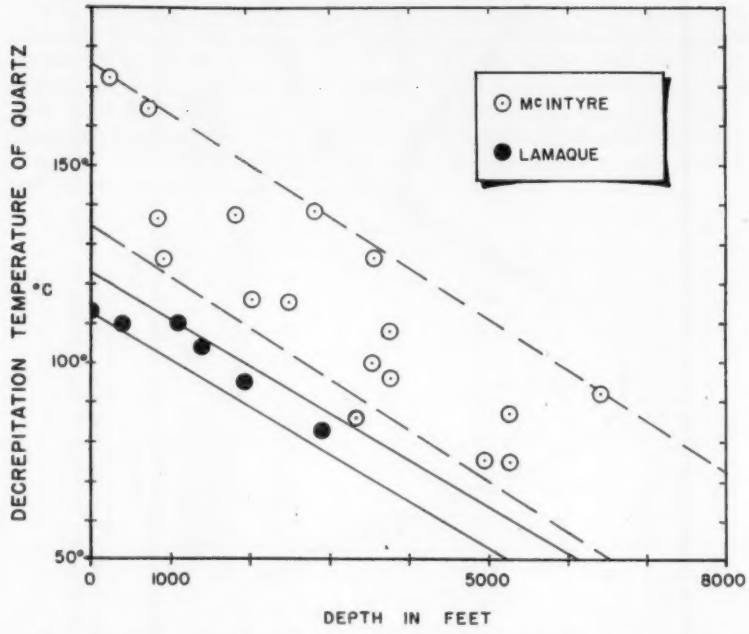

FIG. 2. Temperature of filling of liquid inclusions in quartz (low temperature stage) plotted against depth of occurrence in the McIntyre and Lamaque mines.

DISCUSSION OF THE RESULTS.

If it is assumed that there was no temperature gradient in the low temperature ore-depositing solutions from top to bottom of the McIntyre Mine, and that the solutions were not moving, and were under a pressure due to the rock load above, there would be a decrepitation temperature gradient of approximately 30° C per mile (see P-V-T charts for water given by Béland,[6] Ingerson,[4] Scott [5]), the gradient being in the same sense as that found. If the solutions were moving, the pressure gradient would be greater than the rock load pressure gradient, and also in the same sense. In fact, the speed of the

[6] Béland, R., Synthesis of some sulpharsenites of silver in alkali sulphide solutions: ECON. GEOL., vol. 43, pp. 119–132, 1948.

solutions would be a direct function of the pressure gradient in excess of the rock load gradient.

Of course, it cannot be assumed that there was no temperature gradient, but the available data indicate that it must have been very small. The data given in the previous paper on the ore deposition temperatures in the McIntyre Mine (Smith [5]) are shown in Table 2, along with averages calculated

TABLE 2

TEMPERATURE OF DEPOSITION OF PYRITE IN THE McINTYRE MINE
Mean Values Arranged by Groups of Levels

Levels	No. of samples	Mean low temperature readings
0–1000	15	158.8° C
1000–2000	11	150.8° C
2000–3000	16	148.6° C
3000–4000	43	159.3° C
4000–5000	3	150.0° C
5000–6425	6	133.3° C
General average		154.4° C

from groups of levels. It will be seen that there is no detectable temperature gradient of the low temperature stage of pyrite deposition. It can be assumed with considerable certainty that the deposition of late quartz and recrystallization of early quartz took place at about the same time as the deposition of the late pyrite. Therefore, it is probable that there was an insignificant temperature gradient at that time. This simplifies the calculation of the pressure gradient.

TABLE 3

DECREPITATION TEMPERATURE OF QUARTZ IN THE LAMAQUE MINE

Mine location no.	Depth in feet	Vein no.	Decrepitation temperature
201-82	100	1	113° C
80–13–26	400	13	110° C
12–18–16	1100	18	110° C
15–28S–44	1425	Zone	104° C
20–N–14	1950	Zone	95° C
29–32–E	2900	32	83° C

Since the rock load pressure gradient corresponds to a negative decrepitation temperature gradient of 30° C per mile in the 80° to 175° C range for water, then the driving pressure gradient was equivalent to a decrepitation temperature gradient of about 40° C per mile, or 1.3 times the rock load pressure gradient. This corresponds to a vertical driving pressure gradient of approximately 520 atmospheres per mile (320 g/cm²/cm).

The results prove that the low temperature stage hydrothermal solutions in this mine moved upwards. However, the direction may not have been vertical. The mine workings and vein system plunge 45°, so that if the solutions moved upwards at this angle, as is most likely, the above calculated driving pressure gradient must be multiplied by sin 45° (0.707), converting it to 370 atmospheres per mile (230 g/cm²/cm) up the inclined ore zone.

Another factor must be considered, *i.e.* the horizontal extent of the vein system in a vertical plane which includes the vein system. The specimens were obtained within a distance of 500 feet of the porphyry-lava contact, both in the porphyry and lava. In this total distance of 1,000 feet, it is possible to calculate the pressure gradient on a horizontal line. When this was done it was found that the magnitude of the variation of pressure was approximately equal to that calculated from the scatter of the data shown in Figure 1. In other words, if the solution moved upward at 45° to the horizon, then the iso-baric curves must have been perpendicular to the direction of flow, that is, dipping at 45°. This means a pressure gradient on a horizontal line in a vertical plane which includes the plunging vein system. The quantitative relations are:

$$z = x\left(\cos y \sin y + \frac{\cos^2 y}{\tan y}\right),$$

where z is the horizontal gradient, x is the vertical gradient, and y is the angle of plunge.

The low temperature stage of mineralization at the McIntyre Mine is not a unique occurrence. Many of the other mines in northeastern Ontario and northwestern Quebec have somewhat similar low temperature mineralization. (The areal extent of this low temperature stage and related problems are now being investigated in this laboratory.) The vertical gradient of temperature of decrepitation of the ore of the Lamaque Mine, Bourlamaque, Quebec, was determined in order to substantiate the results from the McIntyre Mine. The group of mined veins plunges approximately 77° south-southwest and is only about 400 feet wide, measured in a horizontal direction in the vertical plane which includes the group of veins. Therefore the expected scatter of decrepitation temperatures would be smaller than the McIntyre values. The measured decrepitation temperatures of the Lamaque quartz, obtained in the same way as for McIntyre quartz, are shown in Table 3, and are shown plotted in Figure 2. The vertical driving pressure gradient, calculated as above, was 430 atmospheres per mile, or 420 atmospheres per mile (260 g/cm²/cm) up the inclined ore zone. This is very similar to the calculated driving pressure gradient in the McIntyre vein system. The calculated scatter of the values (7.5° C) agrees with the observed scatter (10° C).

Using the above technique, it would be possible to map out the flow lines in the plane of a long vein, by first constructing contour lines representing equal driving pressure in the plane of the vein, and then drawing flow lines at right angles to the contour lines.

Another use of the contoured driving pressures in the plane of a vein is in the construction of a diagram showing the relative speed as well as direction of flow of the solutions. The greater the driving pressure gradient, the greater the speed, the relation being:

$$\frac{v_1}{v_2} = \frac{p_1 r_1}{p_2 r_2},$$

where v is the velocity in the center of the fissure, p is the driving pressure gradient, and r is the width of the fissure.

CONCLUSIONS.

A method for determining the direction of flow of hydrothermal solutions consists of (1) a determination of the temperature of deposition in various places in the vein system, in order to establish the temperature gradient, (2) a determination of the filling temperature of liquid inclusions in various places in the vein system, (3) calculation of the relative pressure gradient during deposition, (4) calculation of the relative driving pressure gradient by subtracting the relative rock load pressure gradient, (5) contouring of the relative driving pressures, and (6) construction of flow lines with directional sense perpendicular to the iso-baric lines or surfaces.

It is also possible to calculate the relative speed of flow of the solutions in various parts of a vein during deposition of a given mineral.

ACKNOWLEDGMENTS.

McIntyre Porcupine Mines and Lamaque Mining Company supplied the specimens of ore and kindly allowed publication of the results. The advisory Committee on Scientific Research of the University of Toronto aided this work by grants of money for equipment. I wish to thank Professor G. B. Langford, Dr. M. H. Frohberg, Mr. P. A. Peach, and Mr. A. D. Mutch for critical reading of the manuscript.

GEOCHEMICAL LABORATORY,
DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
Oct. 1, 1949.

REPORT OF THE SUBCOMMITTEE ON GROUND WATER OF THE GENERAL COMMITTEE ON RESEARCH OF THE SOCIETY OF ECONOMIC GEOLOGISTS.[1]

S. W. LOHMAN.

THE foundation for the work of the Subcommittee on Ground Water was well laid in the first report of the subcommittee by its former chairman, the late O. E. Meinzer.[2] Partly because of the pressure of his other duties and partly to better coordinate the work of the subcommittee with that of the Permanent Research Committee on Ground Water, Section of Hydrology, of the American Geophysical Union, Dr. Meinzer in March 1947 asked to be relieved of his duties and suggested that the writer be appointed chairman. Since then the two closely related committees have combined under joint chairmanship in carrying out the excellent plans made by Dr. Meinzer.

In the first report of the subcommittee, Dr. Meinzer presented a digest of his earlier paper [3] that advocated additional research in ground-water hydrology. The suggested fields of research were arranged under nine subheadings, for each of which were given brief statements as to the extent and limitations of our present knowledge and the role that should be taken by the geologist, engineer, physicist, or chemist (working singly or cooperatively) in shedding further light on these problems.

Through correspondence with Dr. Meinzer it was decided that the work of the subcommittee probably could best be carried on by assigning each of the nine topics (and any additional topics that might be suggested) to a man well qualified to prepare a brief but comprehensive report for publication in ECONOMIC GEOLOGY. It was suggested that each such report might indicate (1) work already done, (2) work in progress, (3) additional work that should be done, and (4) methods of implementing the additional work, including suggestions as to institutions or individuals that might do or finance the work.

Considerable difficulty and correspondence were involved in selecting men who are not only well qualified in each subject but who also have the time and inclination to undertake these assignments. In general, however, the response has been very gratifying. The nine research topics and authors assigned are:

(1) *Hydraulics of ground water.*—C. E. Jacob, University of Utah, Salt Lake City, Utah.

[1] This is the second report of the Subcommittee on Ground Water and the 7th in a series of subcommittee reports, all of which were preceded by the "Report of the General Committee on Research of the Society of Economic Geologists," by Charles H. Behre, Jr., Chairman.

[2] Meinzer, O. E., Report on ground water by the Research Committee of the Society of Economic Geologists: ECON. GEOL., vol. 42, no. 7, pp. 672–675, November 1947.

[3] Meinzer, O. E., Suggestions as to future research in ground-water hydrology: Am. Geophys. Union Trans., vol. 28, no. 3, pp. 418–420, June 1947.

(2) *Physics of soil moisture in relation to ground-water recharge, discharge, and storage.*—W. O. Smith, U. S. Geological Survey, Washington 25, D. C.
(3) *Artificial recharge.*—Fred H. Klaer, Jr., U. S. Geological Survey, 445 No. Pennsylvania St., Indianapolis 4, Indiana.
(4) *The geophysics of ground-water head and runoff.*—M. L. Brashears, U. S. Geological Survey, 226 Post Office Bldg., Jamaica 3, New York.
(5) *Geophysical methods of exploration.*—Robert R. Bennett, U. S. Geological Survey, 103 Latrobe Hall, Johns Hopkins University, Baltimore 18, Maryland.
(6) *Geologic texture and structure in relation to ground water.*—Harold E. Thomas, U. S. Geological Survey, 303 Federal Bldg., Salt Lake City 1, Utah.
(7) *Geochemistry of ground water.*—John D. Hem, U. S. Geological Survey, Box 443, Albuquerque, New Mexico.
(8) *Salt-water balance.*—Chester K. Wentworth, Board of Water Supply, Honolulu, Hawaii.
(9) *Bacterial and industrial pollution of ground waters, and the purifying capacities of rocks.*—Carl Wilson, 124 W. Sixth Street, Los Angeles, Calif., and Claude E. Zobell, Los Angeles.

The report on "Geochemistry of ground water" by John D. Hem follows, and reports on each of the remaining eight topics will be published as they are completed. It is hoped that these reports will do much to stimulate research in these several phases of the science of ground-water hydrology, and that through suggestions in these reports will be found institutions and individuals to do or finance the needed research.

U. S. GEOLOGICAL SURVEY,
DENVER, COLORADO,
October 26, 1949.

GEOCHEMISTRY OF GROUND WATER.[1]

JOHN D. HEM.

INTRODUCTION.

THE science of geochemistry is the study of the chemical composition of and actual or possible chemical changes in the crust of the earth. The subdivision of geochemistry concerned with ground water includes study of the nature and amounts of dissolved mineral matter in ground waters, the chemical and geologic changes that influence the kinds and amounts of substances carried in solution, and the chemical relationships between dissolved mineral matter in waters and minerals that make up the rocks in which the waters occur. As thus defined, the field of geochemistry of ground water is very large. Although much work has been done in geochemistry in general, and in some phases of the geochemistry of ground water, the field remains to a large extent unexplored.

CURRENT AND PAST STUDIES.

An extensive summary of the earlier studies in the general field of geochemistry is contained in the works of F. W. Clarke.[2] The latest edition of the "The Data of Geochemistry" was published in 1924. No similar comprehensive summary has been prepared to cover more recent work. Clarke's publication contains only a comparatively small amount of information regarding geochemistry of ground water. Analyses are cited to show various types of natural waters, classified according to the chemical nature of their dissolved solids content. Under the sections discussing the composition and disintegration of rocks and metallic ores, some consideration is given to the action of water in dissolving or depositing mineral matter.

Practically all the minerals that make up the rocks in the earth's crust are soluble in water to some degree, particularly in water containing dissolved carbon dioxide. The important role of water in erosion, in the processes of solution and chemical reaction, as well as in other ways, is well known to every geologist. Minerals are attacked, disintegrated, and dissolved in part or completely by water at the land surface. The action continues in water seeping to the zone of saturation and within this zone wherever the rocks have pore spaces or other openings that may allow water to move through them. As a result of this solvent action, the ground waters of the earth contain dissolved mineral matter taken up in their passage through the rocks. This dissolved mineral matter may be carried long distances in solution, may take part in

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Clarke, F. W., The Data of Geochemistry; five editions: U. S. Geol. Survey Bulls. 330, 491, 616, 695, 770, 1908 to 1924.

chemical reactions with minerals in the rocks, or may be precipitated from solution to form new mineral deposits.

Studies of the geochemistry of ground water require knowledge of the conditions of occurrence of the waters for which analyses are available. This information generally relates primarily to geology and includes the nature and composition of the rock formations through which the water has passed, and the rate of movement of the water through them. A thorough knowledge of chemistry also is required to interpret the water analyses and to correlate them properly with the mineral composition of aquifers. This combination of training is rarely encountered in a single individual. Generally it is necessary that chemists and geologists combine their efforts to explore effectively the geochemistry of ground water.

CHEMICAL STUDY OF NATURAL WATERS.

For many years chemists have been actively engaged in the study of the composition of natural waters. Evidence of the continuing interest and activity in this field is found in the large number of articles under the subject "Natural Waters" which are referred to annually in "Chemical Abstracts." The annual index volumes for this publication in recent years have each contained on the average more than 200 references to articles on natural waters. The articles abstracted appeared in publications throughout the world. A considerable amount of additional work is done each year for which results are not published.

It is necessary to know the chemical character of water that is to be used as a public supply, for industrial purposes, or for irrigation, if such uses are to be made intelligently with necessary allowances for the effects of dissolved substances contained in the water. Most studies of water quality have been made with the direct aim of determining the usefulness of waters for specific purposes. The analyses made in connection with these studies over the years provide a large amount of water-quality data. In some instances, however, the analyses made in special studies do not have a wide general application. For example, large numbers of analyses consisting mainly of determinations of fluoride have been made in some areas in connection with studies of domestic water supplies. Where water analyses are limited to one or two determinations, they have little value beyond providing answers to the specific problem for the study of which they were made. Further, there are large areas in the United States where little is known of the quality of water supplies. Hence, even though many water analyses are available for study, much remains to be done in this field.

Expression of Water Analyses.—The units and forms in which water analyses are expressed remain somewhat varied, but a closer approach to general agreement is being reached. In earlier times, analyses were commonly expressed in concentration by weight of combined salts per unit volume of solution, for example, as calcium sulfate or sodium chloride in grains per gallon. The acceptance of the ionic theory of solutions finally led to the expression of water analyses in concentrations by weight of each ion present in solution. Substances believed to be present in undissociated (nonionized) form present

difficulties of expression. Silicon is generally reported as the oxide, SiO_2, and is the most important substance believed to be contained in undissociated form in the usual types of waters. Iron and boron are generally expressed in terms of the concentrations of the individual elements. It is not known in all cases if these substances are present in dissociated or undissociated form. The units of expression for all constituents generally are parts per million on a weight basis. For certain studies it may be more convenient to express analyses in such units that equal concentrations of different ions will be chemically equivalent. Stabler [3] many years ago advocated the use of units of this type, to which he applied the term "reacting values," for expression of water analyses. Considerably before that time such units had been used abroad and later were widely used in the United States. The term "equivalents per million" for these units has recently been universally adopted in this country to standardize the terminology of water analyses. Parts per million may be converted to equivalents per million by dividing the parts per million value for each ion by the combining weight of that ion.

The expression of water analyses in equivalents per million exclusively, however, meets with an important difficulty. As has been mentioned, considerable uncertainty still exists as to the extent of dissociation of certain substances in solution in natural waters. For example, silica, supposedly not carried in solution in ionized form, cannot be expressed in equivalents per million. The silica content of water should be considered in any geochemical study because of the importance of the compounds of silicon in the composition of rocks.

Classification of Waters.—In the study of water analyses it is generally apparent that certain waters resemble each other in their content of dissolved matter. Some waters may contain the same amounts of certain substances and others may resemble each other in containing predominantly the same ions, although possibly in differing concentrations. From these resemblances the deduction can often be made that the sources of the dissolved matter in the different waters may have been the same, or similar. The similarities or differences in water analyses are of great importance in geochemical studies. To one experienced in the study of water analyses such similarities or differences are often apparent, but a system of classification of the analyses generally is needed to bring out more clearly the resemblance or lack of resemblance among analyses.

For many years it has been common practice to classify waters on the basis of the relative amounts of the substances present in solution. The early practice of reporting analyses in hypothetical combinations was a means of doing this. The hypothetical combinations were computed according to a variety of systems, and analyses expressed in this way did not generally provide accurate knowledge of the chemical character of the water. A water may better be classified on the basis of the equivalents per million of the various substances present. Thus a water which contains principally sodium and chloride may be called a sodium chloride water. More detailed systems of classification of

[3] Stabler, Herman, The mineral analysis of water for industrial purposes and its interpretation by the engineer: Eng. News, vol. 60, p. 335, 1908.

waters may have been worked out and applied by various investigators. Clarke [4] used a system of reporting each ion in terms of its percentage of the total dissolved solids in parts per million. Analyses reported in this manner show relative amounts of dissolved substances and total concentrations, but not the individual concentrations of each ion. Equal percentages of different substances expressed according to Clarke's system are not chemically equivalent; consequently, analyses expressed in this form will not show clearly the chemical character of a water. Palmer [5] suggested classifying waters on the basis of their dissolved solids expressed in "reacting values" or equivalents per million. Further work along this line was done by Emmons [6] in his study of ore deposits. Emmons used a system of trilinear plotting of water analyses. Mills and Wells,[7] as did a number of other investigators, used a system of classification similar to that of Palmer. Subsequently, other investigators have developed systems of classification of waters based on percent equivalents. Such systems have been suggested by Hill,[8] Langlier and Ludwig,[9] and Piper.[10] Essentially these systems group the determined constituents into six groups, three of positive ions and three of negative ions. By trilinear plotting an analysis can be expressed as a single point on a diagram, and relations between different waters of an area and the changes occurring in waters may be studied with relatively simple graphical methods.

The graphical system of Collins [11] is based on equivalents per million rather than percent equivalents and has been used in many publications of the Geological Survey. Systems of expressing analyses graphically contain the defects of the expression of analyses in equivalents per million and in addition they tend to oversimplify the analyses by grouping some of the constituents together.

CHEMICAL INTERACTION OF WATER AND ROCK MINERALS.

The chemical reactions occurring when water comes in contact with rock minerals have generally received study from those whose principal interest was in geology, or who were interested primarily in the changes brought about in the rocks by such reactions rather than the changes that might occur in the composition of the water at the same time. As has been mentioned, water plays a large part in the decomposition of rocks. The action of water in attacking minerals, leaching out soluble products, and leaving insoluble residues

[4] Clarke, F. W., The data of geochemistry: U. S. Geol. Survey Bull. 770, pp. 64–68, 1924.

[5] Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 1911.

[6] Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, 1911.

[7] Mills, R. V. A., and Wells, R. C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geol. Survey Bull. 693, 1919.

[8] Hill, R. A., Geochemical patterns in Coachella Valley: Am. Geophys. Union Trans., Part I, pp. 46–49, 1940.

Hill, R. A., Salts in irrigation waters: Am. Soc. Civ. Engrs. Proc., vol. 67, pp. 975–990, 1941; vol. 68, pp. 1,478–1,493, 1942.

[9] Langlier, W.F., and Ludwig, H. F., Graphical methods for indicating the mineral character of natural waters: Am. Water Works Assoc. Jour., vol. 34, pp. 335–352, 1942.

[10] Piper, A. M., A graphic procedure in the geochemical interpretation of water analyses: Am. Geophys Union Trans., Part VI, pp. 914–928, 1944.

[11] Collins, W. D., Graphic representation of analyses: Ind. and Eng. Chemistry, vol. 15, p. 394, 1923.

behind is recognized as a very important process in erosion and the disintegration of rocks into soil. Under some conditions water may be of importance in metamorphism. Textbooks on rocks contain descriptions of many of these reactions [12] and some of the reactions have received considerable attention from research men.

Water may carry off some rock minerals by simple solution. Calcium sulfate (gypsum) and sodium chloride (halite) are readily soluble in water and are not decomposed in the process. An elementary example of the decomposing effect of water on rock minerals is the solution of calcium carbonate. This mineral is found in many types of rock and is the principal conponent of limestone. Water containing carbon dioxide readily attacks calcium carbonate according to the reaction:

$$CaCO_3 + H_2O + CO_2 = Ca(HCO_3)_2$$

The calcium bicarbonate formed is soluble and exists only in solution. The reaction is reversible. A somewhat more complex example of the effects of water on rocks is the decomposition of a feldspar (orthoclase) to kaolinite and other products.[13]

$$\underset{\text{(Orthoclase)}}{2KAlSi_3O_8} + 2H_2O + CO_2 = \underset{\text{(Kaolinite)}}{H_4Al_2Si_2O_9} + 4SiO_2 + K_2CO_3$$

The potassium carbonate is the only readily soluble product of this reaction and the potassium may take part in further reactions with rock minerals after it is taken up in the water.

Some of the earlier research on the more complex subject of reactions between rock minerals and the dissolved matter already contained in water in contact with them was done in the discovery and study of base exchange. About 100 years ago Thompson [14] and Way [15] discovered that certain soils had the power to remove and retain the bases of alkali salts dissolved in water passed through them, and to replace the bases removed with calcium. This is the process of base exchange later found through extensive studies to be reversible and of common occurrence in nature. A brief outline of some of the earlier work in the field is contained in a paper by Renick [16] which also discusses the natural softening of ground water by silicate minerals. The studies of base exchange have explored one field of the chemical relationships, between minerals dissolved in water and minerals of associated rock formations. Soil chemists also have been most active in the study of base exchange reactions.[17] A large number of minerals have been found to take part in base-exchange re-

[12] Pirsson, L. V., and Knopf, Adolph, Rocks and rock minerals, 3rd ed., John Wiley & Sons, New York, 1947.

[13] Pirsson and Knopf, op. cit., p. 34.

[14] Thompson, H. S., On the absorbent power of soils: Roy. Agr. Soc. Jour., vol. 11, pp. 68–74, 1850.

[15] Way, J. T., The power of soils to absorb manure: Roy. Agr. Soc. Jour., vol. 11, pp. 313–379, 1850.

[16] Renick, B. C., Base exchange in ground water by silicates as illustrated in Montana: U. S. Geol. Survey Water Supply Paper 520, pp. 63–68, 1924.

[17] Kelly, W. F., Cation exchange in soils; Amer. Chem. Soc. monograph no. 109, 1948.

actions. Some of these minerals are listed by Sullivan.[18] The extensive work that has been done in the study of base exchange was no doubt inspired to some extent by the commercial possibilities that the reaction offered in the field of water softening. Basic research in this field also has been done by chemists interested in the reactions taking place in the soil, an understanding of which is often essential in successful agriculture.

Investigations of the origin of ore deposits often have included studies of the action of ground water in altering minerals or depositing them from solution. The conditions under which ore minerals are deposited, however, are not commonly found in circulating ground waters, and these studies are of importance only in a few areas in the general consideration of the geochemistry of ground waters. Among papers related to this field, a report by Ingerson [19] might be cited as an example.

An excellent example of a study of geochemistry of ground water conducted by chemists and geologists is the work at Steamboat Springs, Nevada. A preliminary report on this work has been published.[20]

A specialized field related to geochemistry of ground water is geochemical prospecting. One technique in the field is the determination of trace minerals in water as a key to location of ore deposits. Work in this field is being done by the Geological Survey in the United States under the direction of H. E. Hawkes, and research is being conducted in this field in several other countries, notably in Russia.

APPLICATION TO GROUND-WATER HYDROLOGY.

Within the general field of ground-water hydrology, many studies relating to geochemistry of ground water have been and are currently being made. The water analyses included in most ground-water reports of the Geological Survey have been classified with reference to the rock formations from which the waters come, although such correlations have not always been made rigorously enough to be of much value in extending the basic knowledge of the chemical characteristics to be expected in water from different types of rocks. The identification of mineral particles in aquifers by use of the microscope and the correlation of these results with the chemical analyses of waters obtained from the aquifers constitute a refinement of older methods that should add much to basic knowledge of the geochemistry of ground water. Such studies are being conducted by the Geological Survey in Alabama as reported to the author by Philip E. La Moreaux under whose direction the work is being done. Studies of this type may show, for example, the minerals contributing a particular ion such as fluoride to a water.

[18] Sullivan, E. C., The interaction between minerals and water solutions with special reference to geologic phenomena: U. S. Geol. Survey Bull. 312, 1907.

[19] Ingerson, Earl, Transportation and deposition of silica, *in* Report of the Committee on research on ore deposits of the Society of Econmic Geologists: ECON. GEOL., vol. 42, pp. 560–562, 1947.

[20] Brannock, W. W., Fix, Philip F., Ginanella, Vincent P., and White, Donald E., Preliminary geochemical results at Steamboat Springs, Nevada: Am. Geophys. Union Trans., vol. 29, pp. 211–226, 1948.

The study of ground-water hydrology involves the determination of sources of ground-water recharge, and generally it is desired to learn, if possible, the amounts of recharge and the direction of movement of ground water. Various methods have been used in determining these factors, and in many investigations the study of chemical analyses of waters has been of considerable assistance. Generally in such work the effects of mixing of waters of differing chemical character are of major interest.

The number of individual projects in which geochemical relationships have helped solve ground-water problems is very large and only a few examples can be cited in this brief paper. Recent ground-water investigations by the U. S. Geological Survey in the Bountiful district in Utah have been brought to the writer's attention by Mr. H. E. Thomas who supervised these studies. In this area chemical analyses were used with considerable success in determining the sources of recharge of artesian aquifers. The sources include warm water rising along a fault, canal seepage and irrigation return flow. The identification of sources of recharge of ground water by chemical analyses has been extensively used in Arizona, particularly in Safford Valley [21] and in the Santa Cruz Basin.[22]

In certain parts of the Safford Valley a considerable amount of leakage of deep-seated waters recharges the shallow aquifers. The leakage occurs mainly in fault zones and is revealed by water analyses and water temperatures in places where faults cannot be clearly traced, as well as where they are evident. In the Santa Cruz Basin chemical analyses of ground waters were used with other data to estimate amounts of recharge contributed to the main basin by ground-water inflows from side basins.

Studies of salt-water intrusion of ground waters in coastal areas are related to this field. A number of such studies have been made—for example, those of Poland and others in California.[23]

In many areas, surface waters and ground waters are very closely interrelated. Most stream flow is maintained in part by discharge of seeps or springs, particularly during low stages. Thus during periods of low flow, many streams reflect the chemical character of under-ground waters. The defining of this relationship is aided by chemical analyses. The study of ground water cannot be definitely separated from the study of surface waters in such areas.

SUGGESTED RESEARCH PROJECTS.

Although many data relating to the study of geochemistry of ground water have been collected, the material is scattered through a large number of publications relating primarily to other fields, particularly ground-water hydrology

[21] Turner, S. F. and others, Ground-water resources and problems of the Safford Basin, Arizona, 1946 (mimeographed).

Hem, J. D., Quality of water of the Gila River Basin above Coolidge Dam, Arizona: U. S. Geol. Survey Water Supply Paper 1104 (in preparation).

[22] Turner, S. F., and others, Ground-water resources of the Santa Cruz Basin, Arizona, 1943 (mimeographed).

[23] Poland, J. F., and Piper, A. M., Geologic features of coastal zone of Long Beach-Santa-Ana area, Calif., with particular respect to ground-water conditions: U. S. Geol. Survey Water-Supply Paper (in preparation).

and geology. As a result, the study is disorganized and it is difficult to determine what progress has been made, what is actually known, and what phases of the geochemistry of ground water need further study. One of the first needs, therefore, is a study of existing data and the preparation of a publication or series of publications summarizing them.

An exhaustive study should be made of existing water analyses for samples collected from various rock formations. On the basis of this study some general conclusions probably could be reached regarding the amount of dissolved mineral matter and the chemical composition of the dissolved matter likely to be found in waters that are associated with various types of igneous, sedimentary and metamorphic rocks. The writer has begun a study of this type. There are some indications that the data available are not complete enough to provide a basis for final conclusions at present, primarily because of lack of definite information as to the lithologic character of the aquifers from which samples of water were obtained for the published analyses. The study will indicate fields where further research is needed. However, some tentative conclusions can probably be drawn.

Another type of study that is needed to utilize more fully the existing information is the compilation of data on mineral composition of rock, and analyses of water samples for some of the more widespread geologic formations. With water analyses for samples from many places in a single formation, it might be possible to draw a number of conclusions regarding the uniformity of the aquifer and the relationship between the minerals in the rock and those dissolved in the water, and regarding rates of solution. The Dakota sandstone is an aquifer that might well be studied in this manner.

Another study that could be conducted with data already available is to devise parallel systems of expressing and classifying water analyses and of classifying rocks based on mineral composition. If such systems could be devised they might aid considerably in simplifying geochemical interpretations of water analyses. All existing systems of classifying water analyses either fail to take completely into account the concept of chemical equivalence or omit from consideration the silica content of the water. This is an unfortunate omission in geochemical problems because of the importance of silica as a constituent of rocks. Ideally a system of classifying water analyses might be evolved that would permit plotting the analyses in graphical form similar to the "geochemical diamond" of Hill,[24] but with areas delineated on the graph for waters typical of different types of rock.

A general correlation probably can be made between rocks of the various igneous types and the chemical character of the waters associated with them. The classification of igneous rocks on the basis of mineral composition [25] gives a series ranging from siliceous granitic rocks containing only or mostly feldspar and quartz to ferromagnesian rocks containing little or no feldspar or quartz.

A close study of the relations of dissolved mineral matter in water and minerals in solid form in associated detrital rocks such as sandstone, shale,

[24] Hill, R. A., Salts in irrigation waters, op. cit.
[25] Pirsson and Knopf, op. cit., pp. 162–163.

conglomerate, and alluvium requires a more careful study of the rocks than generally has been made in the past. The rock classifications in general use for sedimentary types [26] are not entirely based on chemical composition. The usual differentiation in cemented or uncemented sedimentary rocks is based merely on grain size and gives no consideration to mineral composition. In many areas in the Western States at least, uncemented alluvial deposits are not extensively leached and are similar in mineral composition to the rocks from which they were derived. These materials are important aquifers in many areas. As the leaching process in the alluvium continues, however, the soluble matter is gradually extracted and the mineral character of the rock formation changes. In most sandstones the principal source of soluble mineral matter is the cementing material. Completely leached sands are likely to consist of little but silica in the form of quartz. Sedimentary rocks that are chemical precipitates, however, such as limestone and gypsum, are readily correlated with water analyses. Rocks of this type are predominately composed of single minerals with varying amounts of impurities.

Studies need to be made to determine the state of certain substances in solution in natural waters. For example, a study should be made of silica contained in ground waters, particularly at first with reference to the state of the material in solution. This study could be expanded to include investigations of the manner in which silica is dissolved from rocks, and the minerals that are most readily attacked. A study also should be made of the nature of all the dissolved matter in water that contributes to the alkalinity. The practice of reporting all material as bicarbonate may be misleading in some instances, but has been almost universally adopted.

A study is still needed regarding the source of some of the minor constituents dissolved in natural waters. This is particularly true of nitrate, especially in the high concentrations in which it is found in some Western ground waters, and also of boron, fluoride, and selenium.

Detailed studies of the effect on water of certain minerals or combinations of minerals should be made as a part of research in this field. These studies will provide more reliable data on which conclusions regarding the interrelation of chemical composition of rock minerals and of the dissolved matter in water can be based. Many of the data now existing in the literature are not completely reliable, some because the mineral composition of the aquifers has not been studied sufficiently, and some because the waters from one rock formation actually had also been in contact with, and contained dissolved mineral matter from, one or more other formations. Two basic procedures could be used in conducting this reasearch:

1. With proper equipment to provide conditions similar to those in nature, laboratory tests could be conducted, using samples of minerals and combinations of minerals of known composition. Leaching tests of this nature have been made by many investigators. In many instances, however, the conditions of the experiment were not similar to those likely to be found in nature.

[26] Pirsson and Knopf, op. cit., p. 243.

2. By careful selection of study areas, valuable investigations could be made largely in the field. The general plan would be to obtain water and rock samples from certain aquifers in areas where the geology is already well known or could be determined accurately. Special attention should be given to obtaining waters that had been in contact only with the formation in which they were found, so that the effects of minerals from other rock formations would be absent.

A part of studies of this type will be the determination of the chemical character of water entering the ground from either precipitation or surface flow. Surface waters must be considered in connection with these studies because of their close relationship to ground water.

After the development of dependable basic data, further research should be conducted to determine the effects on a water of passing from one rock formation into another and coming in contact with different minerals. Also needing study are the solubilities of various minerals in solutions of other minerals in the concentrations found in natural ground waters. The amount of work that should be done in the field of geochemistry of ground water is extremely large. It is hoped that many systematic studies of the geochemistry of ground waters will be undertaken to provide a better understanding of the source and significance of the dissolved mineral constituents and their relation to geologic problems.

U. S. GEOLOGICAL SURVEY,
ALBUQUERQUE, N. MEX.,
October 26, 1949.

DISCUSSION AND COMMUNICATIONS

ORE AND GRANITIZATION.[1]

Sir: I seek leave to reply to one or two points made by Dr. M. D. Garretty in his recent criticism (ECON. GEOL., vol. 44, no. 7, pp. 625–627, 1949).

Granitization at Broken Hill.—Garretty states that "both the visible granitic rock types and the basic rock types in the neighborhood of the Broken Hill lode are sills which were injected before, or during, the early stages of a period of intense folding which itself preceded the deposition of the lode." Both Dr. H. G. Raggatt and the writer, have, at various times, carefully examined the granitic rocks at Broken Hill under the guidance of Mr. Haddon King, Chief Geologist, Zinc Corporation Ltd., and we have noted the manner in which the foliation in the gneisses parallels in detail the bedding in adjacent sediments. We find it difficult to explain this fact if Garretty's magmatic injection hypothesis is accepted.

E. C. Andrews (1),[2] who certainly cannot be dismissed as having inadequately studied the area, has recently stated:

> *Metamorphism.* The peculiar nature, and disposition, of the intense metamorphism to which the Willyama series have been subjected, suggest that the Broken Hill shield occupies the site of an area of intense metamorphism, produced by great local heating at a considerable depth from the surface under conditions of great pressure. This localized area of intense alteration may be called the Broken Hill Hearth.
>
> The longer axis of the hearth is occupied by the main Broken Hill "lode" and its extensions to the north-east and south-west. The intensity of alteration dies away thence in all directions, especially at right-angles to the trend of the "lode." The clays and claystones occupying the zone of most intense alteration have been changed to sillimanite-garnet-mica-feldspar gneisses, mica-schists, quartz-schists, quartz-mica schists and quartzite-schists markedly pegmatized. Widespread granitization is a notable feature of the metamorphism with the production of aplites and peculiar forms of gneiss, which have been, and still may be, regarded by some workers, as of igneous and intrusive origin.

Anyone who cares to study Andrews' original monograph (2), together with the valuable petrological appendices by Stillwell and Browne, and also Andrews' more recent contribution quoted above, cannot fail to be impressed by the possibility, at least, that granitization, palingenesis, or some such process, has been important at Broken Hill.

It is desired to record that field work does not favor the idea that the amphibolites have resulted from some "basic front" phenomena, and this concept is probably untenable.

[1] Sullivan, C. J., ECON. GEOL., Vol. 43, pp. 471–498, 1948.
[2] Numbers in parentheses refer to Bibliography at end of paper.

Stillwell (2, pp. 376–77) reports that the green feldspar, typical of the pegmatites with which the lode is genetically connected, is also found in the numerous pegmatite veins, knots and lenses, occurring in the granulite (footwall gneiss). 'In fact, there seems to be little evidence that the two pegmatites are vastly different, a fact which rather suggests that the process of granite-formation and its attendant development of numerous pegmatites—which Stillwell (2, p. 377) suggests may have been formed by a process of "metamorphic differentiation"—may, in spite of Garretty's suggestion to the contrary, have been quite closely connected with the formation of the ore deposits.

Many Swedish geologists would undoubtedly call the Broken Hill gneisses migmatites, and one cannot help but be impressed by the similarity between the general geological setting of the Broken Hill lode and that of such deposits as those occurring at Ammeberg, Sweden, recently described by Magnusson (6). According to this author, the deposits have been formed in connection with the palingenesis of sediments and other rocks, and were concentrated ahead of the front of veined gneisses (the migmatite front).

K. C. Dunham (3) classifies, under the heading of "hypothermal with regional-metamorphic environment," the deposits at Falun, Ammeberg, and Boliden (Sweden) with those of Broken Hill.

Although J. K. Gustafson (4) would appear to be right in claiming that the Broken Hill ore was deposited under much lower temperature conditions than those under which the garnet-sillimanite-cordierite rocks were formed, this high temperature metamorphism may yet be related to the later and lower temperature development of widespread pegmatite-injection, which may be connected with the deposition of the ore. Granting these possibilities, studies additional to those of a structural nature may be important in the search for a second lode at Broken Hill—*e.g.*, an examination of the attitude (including pitch) of the metamorphic zones along the lines of the investigation recently carried out in the Scottish Highlands by Q. K. Kennedy (5), together with a study of the distribution of migmatites relative to the ore, would seem to be desirable.

If the possibility is granted that the Broken Hill deposits may have arisen in connection with the ultrametamorphism or granitization of the Willyama sediments, the question naturally arises, where did the lead and zinc come from? In describing the Ammeberg deposits, Magnusson (6, p. 210) says—"In connection with these processes (formation of migmatites) several metals have been driven out from the sediments and from older sulphide ores and concentrated outside the front of the veined gneisses (migmatite front)."

As far as Broken Hill is concerned, there is not yet much evidence as to the source of the lead and zinc. However, it may be deduced that the original sediments were mainly shales and sandstone, some members of which were calcareous, and that some of the sediments may have contained a considerable amount of manganese. The analyses quoted by Andrews (2) show that the garnet sandstone for example contains 14 to 27 percent MnO_2 The rock called a granulite by Stillwell (2), and regarded by him as metamorphosed sandstone, contains approximately 1 percent MnO_2. One specimen

of the sedimentary banded iron quartzite contained 7.08 percent MnO_2 (in the mineral spessartite). Since concentrations of manganese are most commonly accomplished by sedimentary processes, it seems likely that the high manganese content of some of the granitic-looking gneisses of the district was originally contained in the sediments from which these rocks may have been derived. The manganese of the rhodonite and spessartite, which are important gangue minerals in the ore deposit, could thus have been derived from the sediments of the district. Other rock analyses indicate the presence of a considerable amount of P_2O_5 in some rocks while one so-called aplite contains 9.23 percent BaO.

Hence, although there is, as yet, little indication that the original sediments were rich in lead and zinc, the available information does suggest that these sediments may have been of a rather unusual type and that some metals, now in the lode, were originally derived from the surrounding sediments.

Isomorphous Substitution.—Garretty takes an analysis showing the SnO_2 content of a specimen of spinel, and, allowing for the relative proportions of iron and magnesium in the specimen and in Precambrian granite, arrives at the conclusion that a large amount of tin would be absorbed by the granite. It would seem just as logical to conclude that, since some spinels contain up to 30 percent zinc, enormous amounts of this metal could be absorbed by granite. Although the work of several investigators, including that of Sandell and Goldich (7), shows quite clearly that there is a marked relationship between the zinc and iron content of igneous rocks, no such calculations as those performed by Garretty are valid.

Similar remarks apply of course to the lead-potassium relationship question by Garretty. The graphs of the authors mentioned above indicate that lead very probably does substitute for potassium to an extent, but it is abundantly clear that lead does not ordinarily substitute for an indefinite quantity of potassium. Substitution in a particular mineral cannot be applied to a rock as a whole.

Conclusion.—The paper criticized by Dr. Garretty was a preliminary attempt to show that some of the bases on which current theories of ore genesis rest can be interpreted in various ways. However, the alternative ideas suggested are not fully developed and are likely to be modified very considerably, even by the writer. Dr. Garretty has usefully pointed out some weaknesses.

Structural geology has had many successes as an ore-finding tool, and is obviously important, but there has been a tendency to overemphasize the significance of this branch of geology. It is considered that further basic research is necessary before geologists can speak authoritatively concerning the probabilities of finding the metal supplies needed for the future, and the aim of the present papers has been to stimulate, if possible, enquiry and research.

Acknowledgments.—In reply to recent discussion (ECON. GEOL., Vol. 44, p. 344) it was stated that "intensification and extension . . . of the mapping . . . has demonstrated that the ores (in the Cobar-Nymagee district, N.S.W.) are closely related to granite." It is desired to record that there was no intention of claiming this as an original discovery, and it had already been

stated (Vol. 43, p. 495) that "geologists have unanimously attributed the ore to granite occurring at depth." A. C. Lloyd clearly postulated this idea in the Annual Report of the Department of Mines, N.S.W. for 1935, p. 89.

C. J. SULLIVAN.

BUREAU OF MINERAL RESOURCES,
GEOLOGY AND GEOPHYSICS,
CANBERRA, A.C.T., AUSTRALIA,
Sept. 22, 1949.

BIBLIOGRAPHY.

1. Andrews, E. C., Geology of Broken Hill, New South Wales: Symposium on the geology, paragenesis, and reserves of the ores of lead and zinc, 18th Internat. Geol. Congress, London, pp. 117–122, 1948.
2. Andrews, E. C., The Geology of the Broken Hill District: New South Wales Geol. Survey, Mem. 8, 1922.
3. Dunham, K. C., Introduction, Symposium on the geology, paragenesis, and reserves of the ores of lead and zinc, 18th Internat. Geol. Congress, London, p. 10, 1948.
4. Gustafson, J. K., Discussion of geology of Broken Hill: Symposium on the geology, paragenesis, and reserves of the ores of lead and zinc, 18th Internat. Geol. Congress, London, pp. 123–124, 1948.
5. Kennedy, Q. K., On the significance of thermal structure in the Scottish Highlands: Geol. Mag., vol. 85, no. 4, pp. 229–234, 1948.
6. Magnusson, N. H., Zinc and lead deposits of Central Sweden: Symposium on the geology, paragenesis, and reserves of the ores of lead and zinc, 18th Internat. Geol. Congress, London, pp. 206–212, 1948.
7. Sandell, Ernest B., and Goldich, Samuel S., The rarer metallic elements of some American igneous rocks: Jour. Geology, vol. 51, no. 2, pp. 167–189, 1943.
8. Sullivan, C. J., Reply to criticism by A. B. Edwards and A. J. Gaskin: ECON. GEOL., vol. 44, pp. 336–346, 1949.

Sir: It is heartening to see that Mr. Sullivan has not pressed some of his views which were most open to criticism, such as the existence of a "basic front" at Broken Hill. In regard to his reply to my "Discussion," I wish to comment on only one point which has been brought forward. Analysis of Sullivan's isomorphous substitution hypothesis was a reductio ad absurdum, using his own figures. It was made on the basis that quantitative examination of any hypothesis is, if possible, desirable. Isomorphous substitution in specific minerals is not in question. The extension of the principle to the magnesium, iron, and potassium content of igneous rocks was put forward by Sullivan himself (page 486).

M. D. GARRETTY.

NORTH BROKEN HILL LIMITED,
MELBOURNE, AUSTRALIA,
September 22, 1949.

REVIEWS

Minerals of Western Australia, Vol. 1. By EDWARD S. SIMPSON. Pp. 479; figs. 111; tbls. 42. William H. Wyatt, Perth, Western Australia, 1948. Price, £3/7/6.

This is the first of three volumes to appear on this subject. This one covers the minerals from actinolite to chlorite. It appears to be a laborious and painstaking collection of occurrences, locality by locality, where each mineral is known. Calcite, for example, takes up 75 pages, with a brief statement or description of each occurrence. It is a contribution to the knowledge of Australian mineral occurrences, but includes little or no contribution to mineralogy of minerals proper. The mineral properties occupy a sentence or two and some of this is quite out of date.

Principles of Structural Geology, 4th Edit. By CHARLES M. NEVIN. Pp. 410; figs. 250. John Wiley & Sons, Inc., New York, 1949. Price, $6.00.

This 4th edition of a well known textbook shows several changes: a chapter has been added on "Laboratory exercises," references to source material are taken out of the text and are given at the end of the chapters; the text material is expanded and revised, and the back cover carries seven large folded maps. Several new illustrations were observed. The contents, as before, consist of stress and strain relations, physical properties of rocks, flexures and faults, joints and cleavage, structures associated with igneous intrusion and unconsolidated sediments, earth theories, continents and oceans, and mountain systems.

The additions and changes make this edition a more usable textbook.

Introduction to Physical Geology, 5th Edit. By WILLIAM J. MILLER. Pp. 482; figs. 397. D. Van Nostrand Company, Inc., New York, 1949. Price, $4.50.

This edition like the former ones is designed to accompany the author's companion volume "Introduction to Historical Geology." The general form is similar to previous editions but many changes and revisions have been introduced to bring this volume up to date, notably on crystal structure, rocks, earthquakes, volcanism and weathering. Among many new illustrations, one notices many aerial views.

Geology—Principles and Processes, 3rd Edit. By WILLIAM H. EMMONS, GEORGE A. THIEL, CLINTON R. STAUFFER, AND IRA S. ALLISON. Pp. 502; figs. 488; numerous tables; 3 appendices. McGraw-Hill Book Co., Inc., New York, 1949. Price, $4.50.

This new edition carries the same subject matter as before and covers the subjects customarily considered in books of physical geology. This new edition emphasizes interpretation of land forms and structures as observed from the air, both in the text matter and by illustrations, many of which are "bleed." A new discussion of continental shelves and tidewater lands is presented. Also there is given

a discussion of the atom for the benefit of those who lack knowledge of physics or chemistry.

The book is well printed, nicely illustrated and should maintain the good standard of its predecessors.

Howe

Conservation in the United States, 3rd Edit. By A. F. GUSTAFSON, C. H. GUISE, W. J. HAMILTON, JR., AND H. RIES. Pp. 534; figs. 254; tbls. 21. Comstock Publishing Co., Ithaca, N. Y., 1949. Price, $5.00.

This third edition is largely to take stock of changes brought about by World War II. Like its predecessors it includes the Development of Conservation, Soils, Water, Soil Erosion and Conservation, Forests and Forest Lands, Forest Conservation, Grazing Lands, Parks, Fisheries, Game, Wildlife, Economics of Mineral Resources, Metals, Coal, Oil, and Nonmetals. The parts relating to minerals are of necessity rather abbreviated.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Geological Survey—Washington, D. C., 1949.

Bull. 948–B. Chromite Deposits near Seiad and McGuffy Creeks, Siskiyou County, California. FRANCIS G. WELLS, CLAY T. SMITH, GARU H. RYNEARSON, AND JOHN S. LIVERMORE. Pp. 43; pls. 27; figs. 5. *Chromite-rich schlieren in dunite. Indicated and inferred reserves are 274,500 short tons averaging 8% Cr_2O_3.*

Bull. 961. Manganese Resources of the Artillery Mountains Region, Mohave County, Arizona. S. G. LASKY AND B. N. WEBBER. Pp. 86; pls. 28; figs. 4; tbls. 4. *Manganese deposits include: (1) stratified oxide deposits; (2) faults, fissure zones, and breccia zones, cemented with manganese oxide; and (3) supergene vein deposits of oxides with some related replacement bodies. Area estimated to contain a minimum of 200,000,000 tons averaging 3 to 4% Mn.*

Bull. 962–A. Coal Deposits of the Santa Clara District near Tonichi, Sonora, Mexico. IVAN F. WILSON AND VICTOR S. ROCHA. Pp. 80; figs. 3; pls. 12; tbls. 8. *Anthracite to meta-anthracite rank in Upper Triassic-Lower Jurassic sediments. The coal beds lie in two areas separated by the Potrero fault. One area contains 9 and the other 7 beds up to 1 m thick. Possible length of some beds is 1050 m, and some have been explored for 112 m down dip.*

Bull. 964–A. Manganese Deposits of the Serra do Navio District, Territory of Amapá, Brazil. JOHN VAN N. DORR II, CHARLES F. PARK, JR., AND GLYCON DE PAIVA. Pp. 51; pls. 4; fig. 1; tbls. 5. *28 separate deposits of MnO_2 have been found in an area 7 km long and 1 km wide. Country rock probably a series of metasedimentary rocks. Outcrops average 50% Mn. Ranges from 0.04 to 0.25% As. Over 7,000,000 tons of visible, probable and possible ore estimated.*

Bull. 966–B. Geophysical Abstracts 137, April–June 1949. M. C. RABBITT, V. L. SKITSKY, AND S. T. VESSELOWSKY. Pp. 70. *Abstracts nos. 11002 to 11201.*

Prof. Pap. 221–A. The Foraminiferal Fauna of the Upper Cretaceous Arkadelphia Marl of Arkansas. JOSEPH A. CUSHMAN. Pp. 19; pls. 4. *Records 116 species and varieties of Foraminifera from 11 localities of the Arkadelphia marl. Sixty genera are represented.*

Water Supply Papers.

1028. Water Levels and Artesian Pressure in Observation Wells in the United States in 1945. Pt. 6. Southwestern States and Territory of Hawaii. Under the direction of C. G. PAULSEN. Pp. 301; figs. 13.

1073–1074. Water Levels and Artesian Pressure in Observation Wells in the United States in 1946. Under the direction of C. G. PAULSEN. **Pt. 3. North-Central States.** Pp. 366; figs. 7. **Pt. 4. South-Central States.** Pp. 215; figs. 14.

1066. Floods of August 1940 in the Southeastern States. WATER RESOURCES BRANCH. Pp. 554; pls. 22; figs. 35; tbls. 33.

U. S. Bureau of Mines—Washington, D. C., 1949.

Rept. Inv. 4515. Titanium Minerals in Central and Northeastern Florida. J. R. THOENEN AND J. D. WARNE. Pp. 62; figs. 26. *Describes investigations to determine extent and grade of "heavy sand" concentrations in inland dune areas. Holes were drilled in 10 areas. The highest concentrations averaged 1 to 2% heavy-mineral content.*

Rept. Inv. 4519. Production of Ductile Titanium at Boulder City, Nev. F. S. WARTMAN, J. P. WALKER, H. C. FULLER, M. A. COOK, AND E. L. ANDERSON. Pp. 37; figs. 2; tbls. 5. *An account of the production of 100-pound batches of ductile-grade titanium powder, by reduction of purified titanic chloride with magnesium, followed by grinding, leaching, and magnetic separation of reaction product. Apparatus, technique, and methods of controlling product quality are described, and some data on operating costs given.*

Inf. Circ. 7521. Selected List of References on Minerals and Related Subjects. D. G. RUNNER. Pp. 9. *List of standard references in common use and generally available in college libraries.*

Mineral Market Rept. 1783. Distribution of Oven and Beehive Coke in 1948. MAXINE M. OTERO, J. A. DECARLO, AND J. A. CORGAN. Pp. 34; figs. 3; tbls. 4. *The largest tonnage of coke on record (74,214,856 tons) was distributed by coke-plant operators in 1948.*

Geology of the Coast Ranges immediately North of the San Francisco Bay Region, California. CHARLES E. WEAVER. Pp. 242; pls. 14; figs. 2. Geol. Soc. America Mem. 35. New York, 1949. *Discusses in detail the geography, systematic geology, structure, and economic deposits of nine quadrangles in the Coast Ranges of Central California. Contains much valuable information on the Coast Ranges, representing the culmination of work started by the writer in 1903. An extensive bibliography.*

The Study of Rocks, Revised 2nd Edition. S. J. SHAND. Pp. 236. The Macmillan Co., New York, 1949. Price, $2.50. *Revision of an elementary textbook; mineralogical and chemical characters and appearance in the field; chapter on classification.*

Antarctic Conquest. COMMANDER FINN RONNE. Pp. 299; 52 photographs; 6 maps. G. P. Putnam's Sons, New York, October 1949. Price, $5.00. *A vivid and realistic adventure story covering 250,000 square miles, yielding new knowledge of geology, meteorology, seismograph recordings and aerial mapping.*

Illinois State Geological Survey—Urbana, 1949.

Rept. Inv. 143. Petrographic Analysis of Coal by the Particle Count Method. BRYAN C. PARKS. Pp. 48; figs. 14; tbls. 11. *Describes a method of physical analysis of broken coal in terms of banded ingredients, particularly vitrain and clarain.*

Rept. Inv. 144. Atterberg Plastic Limits of Clay Minerals. W. ARTHUR WHITE. Pp. 5; tbl. 1. *Liquid limit, plastic limit, and plastic index of common pure clay minerals presented.*

Circ. 152. Southern Illinois Mineral Resources and Industries. MORRIS M. LEIGHTON AND WALTER H. VOSKUIL. Pp. 31; tbls. 11; figs. 21. *An account of coal, oil and gas, fluorspar, lead-zinc, and other mineral resources. Largely statistical.*

Circ. 154. Illinois Fluid Injection Research Reviewed. FREDERICK SQUIRES. Pp. 12; figs. 35. *Brief descriptions of results of research directed toward the solution of problems arising from the unusual characteristics of Illinois oil sands.*

Press Bull. Ser. 60. Oil and Gas Development in Illinois in 1948. ALFRED H. BELL AND VIRGINIA KLINE. Pp. 52; tbls. 8; figs. 3.

Kansas Geological Survey—Lawrence, 1949.

Bull. 78. Oil and Gas Developments in Kansas During 1948. W. A. VER WIEBE, J. M. JEWETT, AND E. K. NIXON. Pp. 186; figs. 53; tbls. 86.

Bull. 80. Geology and Ground-Water Resources of Pawnee and Edwards Counties, Kansas. THAD G. MCLAUGHLIN. Pp. 189; pls. 9; figs. 12; tbls. 16.

Bull. 82, Pt. 3. Ceramic Utilization of Northern Kansas Pleistocene Loesses and Fossil Soils. JOHN C. FRYE, NORMAN PLUMMER, RUSSELL T. RUNNELS, AND WILLIAM B. HLADIK. Pp. 75; pls. 3; figs. 10; tbls. 7. *Former windblown silts are suitable for manufacture of brick, tile, and ceramic aggregates.*

North Dakota Geological Survey—Grand Forks, 1949.

Bull. 23. Glacial Geology of the Oberon Quadrangle. PAUL RODERICK TETRICK. Pp. 35; pls. 2; figs. 6; tbls. 3.

Bull. 24. The Geology of the Tokio Quadrangle. DAVID G. EASKER. Pp. 35; pls. 2; figs. 7; tbls. 3. *Glacial geology.*

Stratigraphy and Petrology of Buck Hill Quadrangle, Texas. SAMUEL S. GOLDICH AND MORRIS A. ELMS. Pp. 50; figs. 6; pls. 6. Bur. Econ. Geol., Univ. Texas Rept. Inv. 6, Austin, 1949. *Tertiary tuff beds and related sediments with intercalated lava flows, resting unconformably on Cretaceous limestone and clay. Small syenite intrusives.*

Canada Geological Survey—Ottawa, 1948–1949.

Mem. 251. McConnell Creek Map-Area, Cassiar District, British Columbia. C. S. LORD. Pp. 72; pl. 1; map 1. *Area lies in a mountainous, relatively inaccessible region near center of northern half of British Columbia. Permian to Paleocene sediments and volcanics with basic and acid intrusives. Occurrences of gold, silver, copper, coal, and other minerals described.*

Bull. 12. Jurassic Formations of Maude Island and Alliford Bay, Skidegate Inlet, Queen Charlotte Islands, British Columbia. F. H. MCLEARN. Pp. 19; figs. 3. *A stratigraphic description.*

Quebec Department of Mines—Quebec, 1948–1949.

Geol. Rept. 36. Forget Lake Area, Saguenay County. W. W. LONGLEY. Pp. 25; pls. 8; map 1. *Area underlain by Grenville (?) sedimentary series and intruded by gabbro and granites.*

Geol. Rept. 37. Wakeham Lake Area, Saguenay County. JACQUES CLAVEAU. Pp. 58; figs. 2; pls. 18; maps 2. *Geologic mapping of an area in the uplands north of the north shore of the Gulf of St. Lawrence. Quartzites and schists intruded by gabbro and granite.*

Geol. Rept. 38. Upper Romaine River Area, Saguenay County. JACQUES CLAVEAU. Pp. 35; figs. 20; map 1. *Report on reconnaissance survey of the geology along the upper part of the Romaine River and some of its tributaries. Bedrock comprises large masses of anorthosite and granite with less amounts of gabbro, gneisses and sedimentary rocks.*

The Geology and Mineral Deposits of Uganda. K. A. DAVIES AND C. B. BISSET. Pp. 20; pls. 4; maps 2. Mineral Resources Dept., Imperial Institute, London, 1948. *Describes principal geologic formations and occurrences of tin, gold, wolfram, tantalite-columbite, phosphate, salt, and other minerals. Cites future problems.*

Australian Mineral Industry, Economic Notes and Statistics, Vol. 1, No. 4. Pp. 41; numerous tables. Melbourne, 1949. *A paper on "The Opal Industry in Australia" by I. C. H. Croll and general information on the mineral industry—production, imports, exports, and metal prices.*

The Geology of Pietermaritzburg and Environs. LESTER C. KING. Pp 26; fig. 1. South Africa Geol. Survey, Pretoria, 1948. *Survey of 240 square mile area on western side of the Natal monocline. Formations described. Mineral resources restricted to clay and road-metal.*

Sedimentos Neógenos del S. W. del Uruguay. ALFREDO CASTELLANOS. Pp. 35; figs. 4. Univ. Nac. del Litoral Pub. 34, Rosario, Argentina, 1948. *A paleontological study of S. W. Uruguay.*

Estudios Geológicos de Yacimientos Minerales de la Provincia de Jujuy. FEDERICO AHLFELD. Pp. 65; maps and photos. Univ. Nac. Tucuman Pub. 474, Jujuy, Argentina, 1948. *Geologic study of mineral deposits in the Province of Jujuy.*

Minas Gerais Instituto de Tecnologia Industrial—Belo Horizonte, 1948–1949.

Avulso 4. Uraninita no Brasil. WILLER FLORENCIO. Pp. 24; fig. 1; pls. 4. *Uraninite in Brazil.*

Avulso 6. Aguas Termais de Itaú. WILLER FLORENCIO AND CELSO DE CASTRO. Pp. 20. *Springs of the Termas of Itaú.*

Avulso 7. Nova Fonte Radioativa do Barreiro-Arazá, Minas Agua da "Bomba." WILLER FLORENCIO. Pp. 12. *Radioactive springs.*

Avulso 8. Marcha Analítica dos Minerais do Grupo da Betafita. WILLER FLORENCIO. Pp. 16; fig. 1. *Scheme of chemical analysis.*

Bol. 9. Geoquimismo Magmático e Origem dos Batolitos Graníticos. D. GUIMARÃES. Pp. 122. *Geochemistry of magmas and the origin of granite batholiths.*

Departamento Nacional da Produção Mineral—Rio de Janeiro, 1947–1949.

Nota Prel. 46. Contribuição á Geologia dos Estados de Goiás e Mato Grosso. FERNANDO F. M. DE ALMEIDA. Pp. 15; maps 2. *Contributions to the geology of Goias and Mato Grosso.*

Avulso 77. Comércio de Quartzo no Brasil. IRNACK CARVALHO DO AMARAL. Pp. 30; tbls. 3. *Regulations controlling the export of quartz and a review of the trade from 1941 to 1945.*

Bol. 25. Ensaios de Beneficiamento de Minérios. JAYME B. DE ARAUJO, ROBERTO BORGES TRAJANO, FRANK E. NOE, JOSÉ GUILHERME DE CARVALHO, AND ALVARO DE PAIVA ABREU. Pp. 125; numerous figures. *Four papers dealing with treatment of ores from Brazilian mines.*

Bol. 83. Relatório da Diretoria 1947. ALBERTO ILDEFONSO ERICHSEN. Pp. 162. *Annual report on the Brazilian mining industry. Descriptions with maps, etc., of many deposits.*

Bol. 124. Um Anfibio Labirintodonte da Formação Pedra de Fogo, Estado do Maranhão. LLEWELLYN IVOR PRICE. Pp. 32; pls. 3. *A Labyrinthodont Amphibian from the Pedra de Fogo Formation, State of Maranhão.*

Bol. 126. Folha do Rio de Janeiro. ALBERTO RIBEIRO LAMEGO. Pp. 16; pls. 7; map 1. *Geologic map of Rio de Janeiro—scale 1:100,000—and description.*

Bol. 127. Caracteres Fisicos e Geológicos da Bacia do Paraiba. RAIMUNDO RIBEIRO FILHO. Pp. 55; figs. 7; map 1. *Physical and geological characteristics of the Paraiba Basin.*

Minerales No. 29. Pp. 43; figures. Inst. de Ing. de Minas de Chile, Santiago, 1949. *2 papers; on boring in the Province of Arauco and on alloys of aluminum as well as business reports.*

Politecnico di Milano—1948–1949.

Pub. 63. Sulla Possibilità d'Impiego dei Restitutori Multipli nei Rilievi a Scala Media. L. SOLAINI AND A. MARAZIO. Pp. 16; tbls. 3; figs. 6. *Photogrammetry.*

Pub. 64. Misure di Gravità Relativa Eseguite Lungo la Linea di Livellazione Genova-Piacenza nel 1947. L. SOLAINI, M. CUNIETTI, C. MAZZON, AND B. RADICA. **Determinazione delle Costanti dei Pendoli dell'Apparato Gravimetrico Conyngham dell'Istituto Geografico Militare.** C. MAZZON. Pp. 34; tbls. 3; figs. 7. *Measurement of gravity along a line of the Italian fundamental geometric levelling between Isola del Cantone and Piacenza in 1947. Determination of the pendulum constants of the Conyngham gravimetric apparatus of the Military Geographic Institute.*

Pub. 65. Studio della Triangolazione Aerea Spaziale Eseguita con il Periscopio Solare (Metodo Santoni). A. MARCANTONI AND L. SOLAINI. Pp. 39; fig. 1. *After a short introduction to explain solar aerial triangulation, errors in solar and periscopic elements of camera orientation, and the distribution of errors in the aerial polygon are studied.*

Enchimento das Fendas de Dissolução dos Calcários de Santa Clara (Coimbra). G. SOARES DE CARVALHO. Pp. 20; figs. 3. Coimbra, Portugal, 1949. *Sand and clay filling of solution cracks in limestone.*

Notícia sobre os Seixos Polidos do Conglomerado Antracolítico da Serra do Buçaco. G. SOARES DE CARVALHO. Pp. 3. Coimbra, Portugal, 1949. *Polished pebbles in conglomerates of Serra do Buçaco.*

Bulletin du Service Géologique du Congo Belge et Ruanda-Urundi No. 4, 1948. Pp. 78. Léopoldville, 1949. *4 papers; on bore holes near Léopoldville; calcareous cement of certain sandstone and quartzites; limestone alteration; and the association of quartz with laterite.*

Carte Géologique du Katanga Méridional. Comité Spécial du Katanga, Op. 15, Bruxelles, 1949. *Geologic map of southern Katanga on scale of 1:1,000,000, accompanied by 24 page report.*

Technische Gesteinsnamen. KARL KRUGER. Pp. 16. Berlin, 1949. *A proposal of new rock names for technical purposes.*

SCIENTIFIC NOTES AND NEWS

STUART ST. CLAIR, Consulting Geologist and Engineer, has returned to New York after "20,000 miles over Africa" by air "safari." Overseas Consultants, Inc., of New York City and the engineering firm of Sir Alexander Gibb & Partners of London was retained by the British Colonial Office to conduct a reconnaissance survey of a proposed connecting link between the Rhodesian and East Africa Railway Systems. St. Clair assessed the mineral potential along and adjacent to the survey route. The party covered all of Tanganyika and much of Kenya, Nyasaland, Northern and Southern Rhodesia, and a little of Belgian Congo and Portuguese East Africa.

THOMAS M. BRODERICK says that he has reserved a limited number of reprints of his address as retiring president of S. E. G., published in the August 1949 number of this Journal. Several mining company geologists have expressed the wish that those men in their organizations who formulate exploration policies and direct their execution, be given the opportunity to read the article. If the names of such men are sent in to Mr. Broderick, he says he will try to distribute his remaining reprints to the best advantage.

HARRY J. WOLF, Mining and Consulting Engineer, announces that he is engaged in professional practice at 420 Madison Avenue, New York 17, N. Y.

JOHN G. BROUGHTON has been made New York State geologist. He had been assistant state geologist.

JAMES S. DODGE, JR., employed by the Natural Resources Section, GHQ, SCAP, Tokyo, Japan, since September 1946, has resigned as deputy chief, mining and geology division, following completion of a draft for the report "Manganese Resources of Japan" to take graduate studies in economic geology at Stanford University.

MURL H. GIDEL, chief geologist of the Anaconda Copper Mining Co., has been elected president of the Alumni Association of the Montana School of Mines for the ensuing year.

E. N. PENNEBAKER was in South Africa until the end of 1949 reviewing geological and exploration problems for the O'okiep Copper Co.

CHARLES H. BURGESS, mining consultant and geologist, succeeded EVAN JUST as director of the strategic materials division of ECA on November 14. After more than sixteen months as director, Mr. Just returned to the editorship of Engineering and Mining Journal.

DONALD CARLISLE is a lecturer in the department of geology at the University of California at Los Angeles.

PHILIP J. SHENON is now in Salt Lake City filling the post of chairman of the division of mineral engineering at the School of Mines of the University of Utah.

HUGH S. SPENCE has retired from the Mineral Resources Division, Canadian Bureau of Mines, after 39 years of service. A specialist in a wide range of industrial minerals and an authority on radioactive minerals, he intends to engage in private consulting practice, at 222 Argyle Ave., Ottawa, Ont.

COL. L. C. HILL, of London, has been elected President of the Institution of Mining and Metallurgy for the Session 1950–51, and will take office at the Annual General Meeting to be held on 18 May next.

JOHN K. GUSTAFSON has resigned as Manager of the Atomic Energy Commission's Raw Materials Operations Office to become Consulting Geologist of the M. A. Hanna Company of Cleveland. He is succeeded by JESSE C. JOHNSON.

The Executive Committee of the International Union of Crystallography has accepted an invitation from the Swedish National Committee to hold the Second International Congress on Crystallography and the Second General Assembly of the Union in Stockholm from June 27 to July 3, 1951. These dates have been chosen in consultation with the Swedish National Committee and with the National Committees of all the countries which adhere to the Union. It is hoped that this early notice will make it possible for those interested in crystallography and its related fields to arrange to attend. Further information can be obtained from the General Secretary of the Union, Dr. R. C. Evans, Cavendish Laboratory, Cambridge, England.